



Hierarchical Interactive Theater Model (HITM):

An Investigation Into The Relationship Between

Strategic Effects And OODA Loops

THESIS

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ABSTRACT (Maximum 200 Words) This effort focuses on understanding the nature of strategic effects. This is done by looking at what strategic effects are, how they can be achieved, and why they are so difficult to simulate. A basis for strategic effects is established in the classical military theories of Clausewitz. Then, using modern military theories of Warden and Boyd, several approaches to simulating strategic effects, with an emphasis on Complex Adaptive Systems techniques, are investigated. Using these concepts as a foundation, an exploratory simulation model called the Hierarchical Interactive Theater Model (HITM) is constructed and exercised. HITM output depicts a cascading deterioration in force effectiveness and eventual total collapse resulting from destruction of vital targets. This outcome is consistent with the expected results of strikes against centers of gravity defined in Air Force doctrine. In addition, analysis of experiments using HITM suggests Observe, Orient, Decide, and Act (OODA) Loops are an effective way to simulate strategic effects at the operational level of war.				
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THESIS

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Degree of Master of Science in Operations Research

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An Investigation Into The Relationship Between
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Richard K. Bullock

TABLE OF CONTENTS

ACKNOWLEDGMENTS	v
LIST OF FIGURES	viii
LIST OF TABLES	ix
ABSTRACT	x
1. Introduction	1
1.1 Background	1
1.2 Research Approach	2
1.3 Scope	3
1.4 Overview	3
2. Strategic Effects	4
2.1 The Fog of Strategic Effects	5
2.1.1 Defining Strategic Effects	5
2.1.2 Clausewitz	10
2.2 Assessing and Modeling Strategic Effects	12
2.2.1 Current Approaches	12
2.2.2 The New Sciences	14
2.2.3 Complex Adaptive Systems	15
3. Hierarchical Interactive Theater Model (HITM)	24
3.1 HITM Background & Overview	24
3.2 HITM Battlespace	26
3.3 Agents	29
3.3.1 Commander	33
3.3.2 Operations	36
3.3.3 Attack Aircraft Pilot	39
3.3.4 Defensive Aircraft Pilot	41
3.3.5 Ground Units	44
3.4 HITM Simulation & Limitations	47
4. Experiments	49
4.1 Equal Fight	49
4.1.1 Results and Analysis	50
4.2 Sensitivity to Initial Conditions	59
4.2.1 Results and Analysis	59
5. Conclusion	63
5.1 Strategic Effects and OODA Loops	63
5.2 Contributions of Research	64
5.3 Areas for Continued Research	64

BIBLIOGRAPHY	66
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LIST OF FIGURES

Figure 1. Concept of Strategic Effects	5
Figure 2. Warden's Entity Model	7
Figure 3. Concept of Emergence	16
Figure 4. OODA Loop.....	17
Figure 5. Hierarchically Linked OODA Loops	19
Figure 6. OODA Web	20
Figure 7. Emergent OODA Loop	20
Figure 8. OODA Loop Advantage Model.....	25
Figure 9. OODA Loop Advantage Simulation.....	25
Figure 10. HITM Battlespace	27
Figure 11. F-16 Fighting Falcon.....	29
Figure 12. HITM Chain-of-Command	30
Figure 13. Generic Agent OODA Loop	31
Figure 14. Decision Cycle Time Degradation Curve	32
Figure 15. Commander's Decision Cycle	33
Figure 16. Commander Decision Criteria	34
Figure 17. Decision Cycle for Operations.....	36
Figure 18. Attack Pilot Decision Cycle.....	38
Figure 19. HITM Attack Aircraft	40
Figure 20. Defense Pilot Decision Cycle	41
Figure 21. HITM Defensive Aircraft.....	42
Figure 22. Ground Unit Decision Cycle.....	43
Figure 23. HITM Agent Interaction Diagram.....	45
Figure 24. HITM Screen Shot	46
Figure 25. Equal Fight Output Variation.....	51
Figure 26. Paths to Victory.....	51
Figure 27. General FLOT Path Characteristics	52
Figure 28. Regions of a Nonlinear System.....	53
Figure 29. FLOT Regions.....	54
Figure 30. MOP Ratio Variance at Transition Boundaries	55
Figure 31. OODA Loop, Resources, and Objective Relationship.....	57
Figure 32. Time to Achieve Objective	60
Figure 33. Ground Win Ratio.....	61

LIST OF TABLES

Table 1. Airpower Theories and Theorists	6
Table 2. Instant Thunder Target Sets	8
Table 3. Warfare as a Complex Adaptive System.....	22
Table 4. Measures of Performance.....	50
Table 5. Basic Statistics of Equal Fight Simulation Runs.....	50

ABSTRACT

Airpower's strength lies in being able to quickly strike the enemy directly where they are vulnerable while being unhampered by geography and surface forces. Airpower theory suggests the effects of these strikes propagate throughout an opponent's military system yielding catastrophic output or strategic effects. Despite this theory being a cornerstone of US Air Force doctrine, current Air Force models do not seem to capture airpower's inherent strength. Since these models are used to support budgetary decision making, the United States may not be funding the airpower capability it needs.

This effort focuses on understanding the nature of strategic effects. This is done by looking at what strategic effects are, how they can be achieved, and why they are so difficult to simulate. A basis for strategic effects is established in the classical military theories of Clausewitz. Then, using modern military theories of Warden and Boyd, several approaches to simulating strategic effects, with an emphasis on Complex Adaptive Systems techniques, are investigated. Using these concepts as a foundation, an exploratory simulation model called the Hierarchical Interactive Theater Model (HITM) is constructed and exercised. HITM output depicts a cascading deterioration in force effectiveness and eventual total collapse resulting from destruction of vital targets. This outcome is consistent with the expected results of strikes against centers of gravity defined in Air Force doctrine. In addition, analysis of experiments using HITM suggests Observe, Orient, Decide, and Act (OODA) Loops are an effective way to simulate strategic effects at the operational level of war.

Hierarchical Interactive Theater Model (HITM):
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1. Introduction

*But in war, as in life generally, all parts of the whole are interconnected
and thus the effects produced, however small their cause, must influence
all subsequent military operations...*

-- Carl von Clausewitz

1.1 Background

By most accounts, Air Force combat models do not adequately capture airpower strategic effects. Since these models are used to support budgetary decision making, the United States may not be funding the airpower capability it really needs. The concept of strategic effects predates the birth of flight. Over 2000 years ago in ancient China, Sun Tzu stated the key to victory was striking the enemy in a manner that would preclude the need to fight, or ensure a short, low cost victory if combat occurred. The advent of flight provided the ability to quickly strike an enemy well behind the lines where they are vulnerable while being relatively unhampered by geography or surface forces. Early airpower visionaries like Mitchell and Douhet recognized this connection between airpower and strategic effects. Today strategic effects is a cornerstone of Air Force doctrine. Despite capturing most of the capabilities of airpower, Air Force models do not capture airpower's inherent strategic capability. The reason for this is strategic effects goes beyond putting metal on a target. It relates to the collision of living, reacting forces. Regardless of planning, equipment, or training, one cannot predict with certainty how an enemy will react to attacks. This human element and the widely accepted unpredictability

of human behavior are the reasons strategic effects are not accurately captured in modeling. The relatively recent emergence of the non-linear sciences, such as Complex Adaptive Systems, offer the possibility of identifying and modeling trends in unpredictable systems. Using Complex Adaptive Systems techniques, this thesis explores the nature of strategic effects and ways these effects can be incorporated into combat models.

1.2 Research Approach

A model specifically suited to examine the cascading, indirect effects of air strikes against vital targets called the Hierarchical Interactive Theater Model (HITM) is constructed. Complex Adaptive Systems and agent-based methodologies form the theoretical framework for HITM. HITM creates a scenario involving two equally matched opponents to include identical military chains-of-command, force structure, and force strength. However, the forces have opposed objectives. Autonomous agents, each with its own Observe, Orient, Decide, Act (OODA) Loop, form the ranks at each level of the chains-of-command. The agents have actions which they can carry out in support of the overall objective. Agents at each level react to enemy actions. Each opponent has resources, which are considered targets by the adversary. Agents require the resources to carry out their actions, thus, destroying the adversary's resources denies them freedom to operate. HITM endgame occurs when one opponent achieves its overall objective of capturing the adversary's airbase. Numerous simulation runs are conducted under this equal fight concept. Simulation output is examined for trends and to determine why and when a given side won or lost. Follow-on runs are conducted wherein small changes are

made to one of the opponents. Using this approach, strategic effects due to various target sets and strategic effects attributable to surprise and first strike are explored.

1.3 Scope

This effort centers on understanding the nature of strategic effects. This is done by first looking at what strategic effects are, what causes them, and why they are so difficult to model. Then, promising approaches to modeling strategic effects, with an emphasis on Complex Adaptive Systems techniques, are investigated. The primary work relates to a JAVA implementation of a Complex Adaptive System called HITM. HITM models a conflict between two military forces. The level of detail in HITM is complex enough to provide a sense of realism yet simple enough to allow identification of relationships between objects. HITM is then used in a number of experiments related to strategic effects. The focus is to examine OODA Loops in agent based models as a means to simulate strategic effects.

1.4 Overview

Chapter 2 provides relevant background information. It traces the nature of strategic effects and establishes a theoretical foundation for building HITM. Chapter 3 then describes the details and mechanics of HITM. Next, Chapter 4 outlines experiments using HITM and their results. Finally, Chapter 5 summarizes this work's findings, outlines contributions of this work, and identifies areas for further research.

2. Strategic Effects

Everything in war is simple, but the simplest thing is difficult...

-- Carl von Clausewitz

Strategic Attack, the Air Force's premier statement on the use of airpower for strategic operations, describes strategic effects as "...massed combat effect without necessarily massing combat forces" [AFDD 2-1.2 1998:p16]. This concept is not new. Early airpower theorists such as Italy's General Giulio Douhet, America's Brigadier General Billy Mitchell, and Britain's Air Marshal Hugh Trenchard envisioned the ability to avoid traditional land and sea forces altogether and strike the enemy's industrial and agricultural infrastructure directly [AFDD 2-1.2 1998:p3]. However, despite the timeless traits of strategic effects, this fundamental concept, as it applies to airpower, has failed to find its way into Air Force models [Tighe 1999:p1]. Since these models are used in force structure and weapon system procurement decisions, the Air Force may not be getting credit -- and resources -- for what it can bring to the fight. The reason strategic effects are not adequately implemented in combat models is because there is no accepted standard for modeling strategic effects. This stems from there being no theoretical foundation on which to base assessments of strategic effects. In order to build this foundation, it is first necessary to understand how an enemy is impacted and reacts to attacks -- the nature of strategic effects.

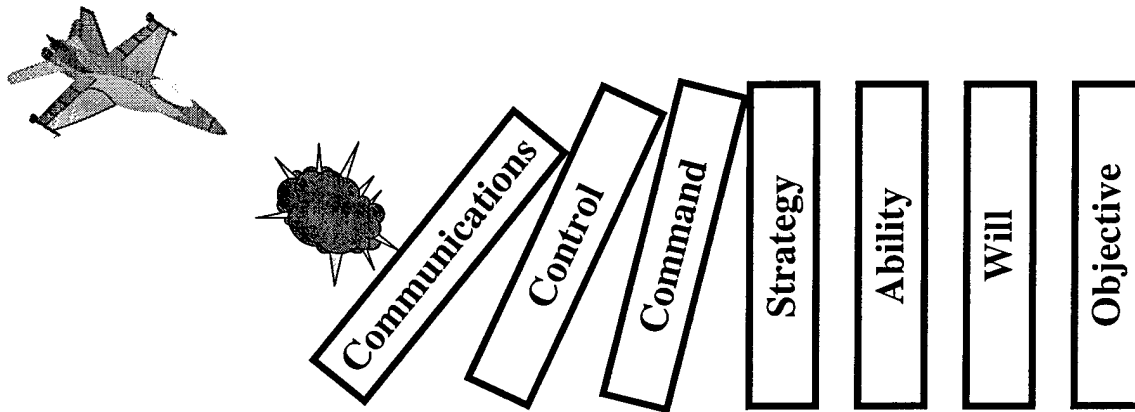


Figure 1. Concept of Strategic Effects

2.1 The Fog of Strategic Effects

Throughout the evolution of airpower strategy, theorists have disagreed on the best way to employ airpower. Even though this debate continues today [Warden 1998:p170], the Air Force has embraced the notion of airpower having the unique ability to deliver "...effects well beyond the proportion of effort expended in their execution" [AFDD 2-1.2 1998:p16]. The following paragraphs trace the nature of strategic effects to understand why such a simple concept is so difficult to model.

2.1.1 Defining Strategic Effects

A strategic effect is the disruption of the enemy's strategy, ability, or will to wage war. There are many methods available to achieve strategic effects. A few examples include withholding economic assistance, naval blockades, or even just the threat of military confrontation. However, the strategic effects discussed here relate to violent military conflict. Specifically, the focus is on strategic effects attributable to destruction of enemy war making processes and materials. In this light, strategic effects can be

Table 1. Airpower Theories and Theorists [Faber 1998]

Theorist	Target(s)	Desired Effect	Political Outcome
Douhet	Population Cities	Revolution	Change government or its behavior
Mitchell	Vital centers	Civil uprising	Change government or its behavior
Harris	Population	Lost will via "Dehousing"	Collapse of opposing state
Air Corps Training School (ACTS)	Key economic nodes	Social collapse	Change government or its behavior
Caproni/ Salvaneschi	Munitions factories	Destroy equilibrium in equipment	Military defeat
Trenchard (1920s)	War materials LOCs	Operational paralysis	Military defeat
Slessor	Troops Supplies Production	Interrupt or destroy equipment and supplies	Military defeat
COA	Munitions Plants	Materiel shortages	Military defeat
EOU	Oil and transportation	Operational paralysis	Military defeat
Schelling	Population (Leadership)	Favorable cost/risk calculations	Change policies
Pape	Military forces	Destroy confidence in military strategy	Yield territory; shift military balance
Boyd	Communications	Lost energy; initiative	Yield territory; Change policies
Warden	Leadership, Organic Essentials, Infrastructure, Population, Fielded Military	Decapitation; Strategic paralysis	Isolate/overthrow leadership
May	Political factions	Promote interest of 1 st faction over others	Change government or its behavior
Link	Attacking military forces	Rapid halt	Military defeat
Lambeth	Military forces	Shape outcomes	Lost capabilities
Owens	Enemy military capabilities	Undermine "New Era Deterrence" with quick response	Unable to coerce the US
Bingham	Enemy maneuver elements	Battlezone isolations and paralysis	Functional military defeat

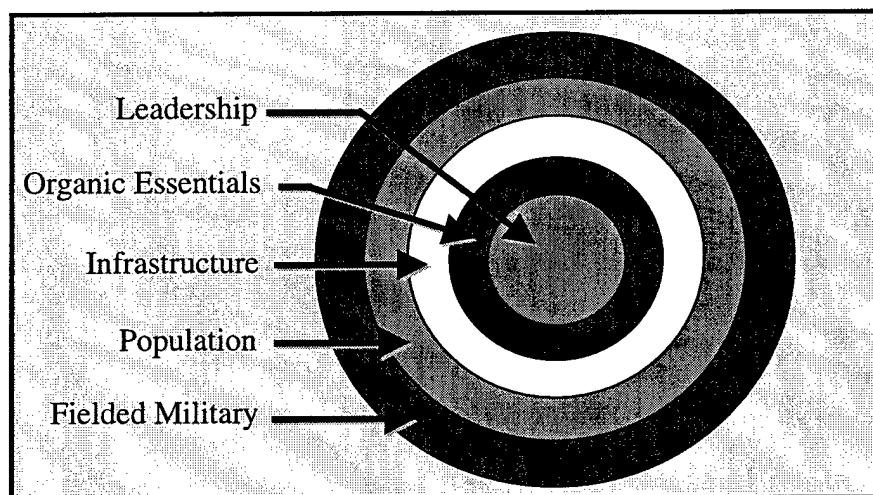


Figure 2. Warden's Entity Model [Tighe 1999:p12]

conceptualized as a cascading or domino effect collapse of the enemy's warfighting capabilities through destruction of vital targets (Figure 1).

The question of which targets to destroy is a source for great debate. Throughout the history of airpower, a wide spectrum of targeting theories has evolved (Table 1). Warden [1995] thinks of the enemy as a system. According to Warden, an enemy system contains key targets that represent the system's centers of gravity. Warden feels these targets represent the enemy's vulnerabilities and if struck, will significantly degrade the performance of the enemy system or even bring it to a halt. To help identify these centers of gravity, Warden uses a generic model of an enemy system (Figure 2). The model is based on the premise that all systems share a common elements. Every system has a leader to give it direction and help it respond to changes in its external and internal environments; each has an energy conversion function to take one form of energy and convert it into another; each has an infrastructure to hold it together; each has entities that populate the system; and each has fielded forces to protect the system.

Table 2. Instant Thunder Target Sets [CINCCENT 1990]

Leadership	Production	Infrastructure	Population	Military Forces
Hussein's Gov't	Electricity	Roads	Military Elite	Air Defense
Telecom & C2	Retail Petroleum	Bridges	Foreign Workers	Offensive air & missile capability
Internal Security	WMD			

The model is composed of five concentric rings with the inner rings being strategically more significant than the outer rings. The rings are hierarchical. Any sub-ring can be broken down into 5 sub-rings. The rings, from the center to the outside are: Leadership, Organic Essentials, Infrastructure, Population, and Fielded Military. Using this model, Warden suggests the enemy's centers of gravity can be identified within each ring and if the appropriate targets are destroyed, preferably simultaneously, both military and political objectives can be attained with limited, traditional military conflict.

Interestingly, nature uses a similar targeting strategy. Recent studies at the University of Michigan found cancers and immune-related diseases follow a hierarchical model when attacking healthy cells. Specifically, researchers found that the bacterium that causes bubonic plague, kills by first cutting the main cellular communications cable and shutting down signaling involved in the immune response. Once cellular communications is cut, attack of the cellular infrastructure begins [UM 1999].

On the other side of the airpower spectrum, Pape [1998] recommends airpower be used strictly to attack theater-level military targets. He claims theater attack would disrupt the enemy's military strategy for controlling disputed territory by destroying fielded forces, interdicting supplies, and disrupting movement and communication. In contrast to Warden, Pape's approach is not to strike strategic targets but to destroy

military forces making the enemy's military ineffective. In short, Pape suggests objectives can be obtained by just attacking Warden's Fielded Military ring. Although the debate continues, Air Force doctrine sides with Warden, as does our operational experience, as evidenced by the target sets identified for the opening scene of Operation Desert Storm, Instant Thunder (Table 2).

History has shown that airpower is extremely difficult to stop. The flexibility of offensive airpower results in a significant advantage over ground forces and enemy air assets, since the defender "...requires more forces to defend a given surface area than the attacker requires to strike a set of specific targets" [AFDD 1 1997:p14]. Thus, airpower has an inherent capability to strike directly at the enemy's centers of gravity, disrupting the enemy's strategy and war sustaining capabilities, avoiding a costly fight through layers of surface forces [AFDD 2-1 1998:p16]. In addition to siding with Warden, Air Force doctrine also views the enemy as a living, warfighting system. This is evident in AFDD 1's description of war:

War is a clash of opposing wills. War is not waged against an inanimate or static object, but against a living, calculating enemy. Victory results from creating advantages against thinking adversaries bent on creating their own advantages. This produces a dynamic interplay of action and reaction in which the enemy often acts or reacts unexpectedly [AFDD 1 1997:p6].

This unexpected, or unpredictable, enemy behavior is a timeless characteristic of warfare. Carl von Clausewitz's writings are generally thought to capture the essence of actual warfare, especially with respect to the unpredictable nature of the enemy.

2.1.2 Clausewitz

War is a violent struggle between rival societies to attain competing political objectives. War is characterized by fear, pain, and suffering and is complicated by effects of weather, terrain, and season. The battlefield is a place of chaos and confusion, where uncertainty and disorder are dominant features [SOS 1998:p4100R1-4]. This essence of warfare is captured in Leo Tolstoy's description of Napoleon's Battle of Borodino:

...As soon as they got out of that exposed space, over which the balls and bullets were flying, their superior officer promptly formed them in good working order, and restored discipline, and under the influence of that discipline led them back under fire again; under the influence of the terror of death they lost all discipline, and dashed to and fro at the chance prompting of the crowd. [Tolstoy 1964:p748]

Because war is a human enterprise, its violence, as portrayed in Tolstoy's description, injects emotion into war which undermines rationality and predictability. No one understood these fundamental truths of war better than Carl von Clausewitz.

Clausewitz is commonly touted as a philosopher more quoted than actually read. His theory on war is captured in the 125 chapters of his book, On War. Some would claim, however, that Clausewitz's work is no theory at all since it lacks the traditional attributes of a theory such as the ability to make predictions [Beyerchen 1992:p1]. Regardless, his writings realistically address war's complexity. Clausewitz is probably most famous for his notion of friction. Clausewitz describes friction as, "...the only concept that more or less corresponds to the factors that distinguish real war from war on paper" [Clausewitz 1976:p119]. He generalizes friction as the force that makes the apparently easy difficult and the countless minor incidents that over time, lower performance, so one always falls short of the intended objective [Sheperd 1997:p3].

Friction can be thought of as war's version of Murphy's Law, "Whatever can go wrong will, at the worst possible moment" [Beyerchen 1992:p10]. This concept of friction lies at the heart of Clausewitz's theory of war. Although friction seems like an intuitive and simple concept, it is actually the source for a great deal of confusion. Clausewitz uses the term friction, or general friction, to refer to two different concepts. The first concept, also called friction, relates to the nonlinear feedback effect leading to the dissipation of energy in a system [Beyerchen 1992:p11]. The second concept, commonly called the "Fog of War," relates to uncertainty.

The first concept, friction, relates to the many unplanned minor events which accumulate to cause actual results to deviate from plan. Watts [1996] suggests friction is an inherent feature of violent conflict and that the balance of friction between two opponents could be manipulated to one's own advantage. Air strikes are an example of how an opponent could induce friction on an enemy. Watts also suggests that "decision cycle times" can be used to gauge the friction on both sides of the conflict and the side with the lowest relative friction, and thus the quickest decision cycle, will have the advantage. Although air strikes certainly create friction for the enemy, how much friction can an air strike create? This uncertainty leads to Clausewitz's second concept of general friction, the "Fog of War".

There are several levels to the "Fog of War". "Fog of War" relates to uncertainty about: the enemy (intentions, forces, objectives), the environment (weather, terrain, danger, exertion), and friendly forces (leadership, intelligence, planning, information, communication) [Sheperd 1997:p7]. Initially, it was proposed that the problem of modeling strategic effects was driven by a lack of understanding of how an enemy was

impacted and reacted to attacks. It was further suggested that this understanding was widely thought to be unattainable because of the unpredictability, or uncertainty, of human behavior. The problem of modeling strategic effects seems to have its roots in Clausewitz's "Fog of War". Specifically, the link is unpredictability about the enemy, unpredictability about the capabilities of friendly forces, and unpredictability about the interaction between the two. Thus, the problem for combat models is how to model unpredictable systems.

2.2 Assessing and Modeling Strategic Effects

Current Air Force models do not seem to capture strategic effects as discussed so far. This was the perception after the Air Force's seemingly poor representation in the 1997 Quadrennial Defense Review (QDR) [Correll 1998:p1]. In the QDR aftermath, Air Force leadership turned to the modeling and simulation community to address modeling of strategic effects in combat models. This effort has stagnated due to, among other issues, difficulty in modeling the human element in warfare and lack of a theoretical framework for incorporating strategic effects. A number of promising methodologies have emerged that can aid in analyzing unpredictable systems and could enhance or replace current combat modeling approaches.

2.2.1 Current Approaches

Some models take into account the effects of air strikes. An example is the Extended Air Defense Simulation's (EADSIM) airbase shock after an initial air strike. However, these models do not capture the cascading effects that ripple through an enemy's system with interactions at every level. Air Force doctrine is based on the

premise that destruction of critical centers of gravity will cause paralysis in the enemy system, degrading their ability to wage war, to include their will to prosecute war. Even THUNDER, the Air Force's current campaign level model, does not adequately model strategic effects [Tighe 1999:p38]. Beyerchen [1992] suggests the problem is that in our effort to understand phenomenon we "linearize" problems to derive an analytical solution. We do this by decomposing a system into small, understandable pieces, deriving a solution for a single piece, and then multiplying by a factor to determine a solution for the whole. This partitioning process, however, comes at the price of realism. Systems are not always decomposable into independent parts. By decomposing the system, we fail to accurately capture component interaction. These interactions dominate the real world making war unpredictable by analytical means [Beyerchen 1992:p19]. Unfortunately, these interactions are at the heart of strategic effects -- interactions among adversaries, interactions between destroyed enemy targets and the enemy, as well as the cumulative effect of these interactions. In addition, throughout this constantly changing web of interaction, opportunities occur and fade. Regardless of great plans or organization, success, or failure, in war depends on the willingness of combatants to capitalize on those opportunities. [SOS 1998: p4100R10]. Linearization discounts this aspect.

A model is only adequate to the extent it yields trends and insights useful in making better decisions. So, how does one balance the need to capture war's realism, its unpredictability, and still provide decision makers with useful insight? The relatively new field of nonlinear sciences may hold some answers.

2.2.2 The New Sciences

The "old" sciences, or Newtonian sciences, include traditional analysis approaches such as optimization, statistics, and regression. The "new" sciences, on-the-other-hand, relate to non-traditional analysis techniques for rapidly scanning the solution space of a computationally complex problem in order to determine boundaries of behavior and regions where rapid changes occur. These techniques come from fields such as Chaos and Complexity theory, as well as neural networks and genetic algorithms. These new methods are not meant to replace the "old" sciences but to supplement them by providing scientists and analysts with new ways to examine systems.

The new methods are especially well suited for examining the nonlinear dynamics of systems. The new sciences, or nonlinear sciences, offer a different way to view reality [Durham 1997:p4]. The nonlinear sciences offer more insight into the dynamics of system operations and our understanding of the solution space [Palmore 1999:p9]. Nonlinear dynamics arise from repeated interaction and feedback. The initial state of a system provides input to a feedback mechanism which determines a new state for the system. The new state then provides input through which the feedback mechanism determines the system's next state, and so on [Watts 1996:p71]. This is very much in line with the interwoven interactions surrounding strategic effects.

Other aspects, beyond feedback, are also found in these systems. Unpredictability, such as that between the enemy and friendly forces, characterize nonlinear systems. In addition, these systems are sensitive to initial conditions. An immeasurably small change could generate an entirely different history for a system [Beyerchen 1992:p5]. Although this sensitivity makes long term prediction impossible,

long-term trends remain the same [Durham 1997:p32]. The nonlinear sciences provide the ability to explore unpredictable systems and understand the initial conditions that drive various long-term trend behaviors [Palmore 1999:p11]. This suggests one could model an enemy system and investigate which initial conditions, such as air strikes, result in achieving desired objectives. One of the most promising of the nonlinear sciences that offers the potential to model an enemy system, is the field of Complex Adaptive Systems.

2.2.3 Complex Adaptive Systems

Complexity theory studies the behavior of simple interacting parts that evolve and adapt to a changing environment. A subset of Complexity theory is the field of Complex Adaptive Systems. A complex system is a set of elements that are interconnected so that changes in some elements, or their interrelations, produce changes in other parts of the system and the entire system exhibits properties and behaviors that are different from those of the individual parts [Jervis 1998:p1]. These systems are usually arranged in a hierarchical fashion with decentralized control, similar to a military chain-of-command. The adaptive portion means coping "at the time" by taking in external factors, building a new strategy, assembling new ingredients, and proceeding [Davis 1997:p31]. Combination of these imply a system of elements where individual elements make their own decisions.

The basic building block of a Complex Adaptive System model is the adaptive, autonomous agent. Adaptive, autonomous agents attempt to achieve a set of goals in an unpredictable, dynamic environment. The agents are adaptive in that their decisions and

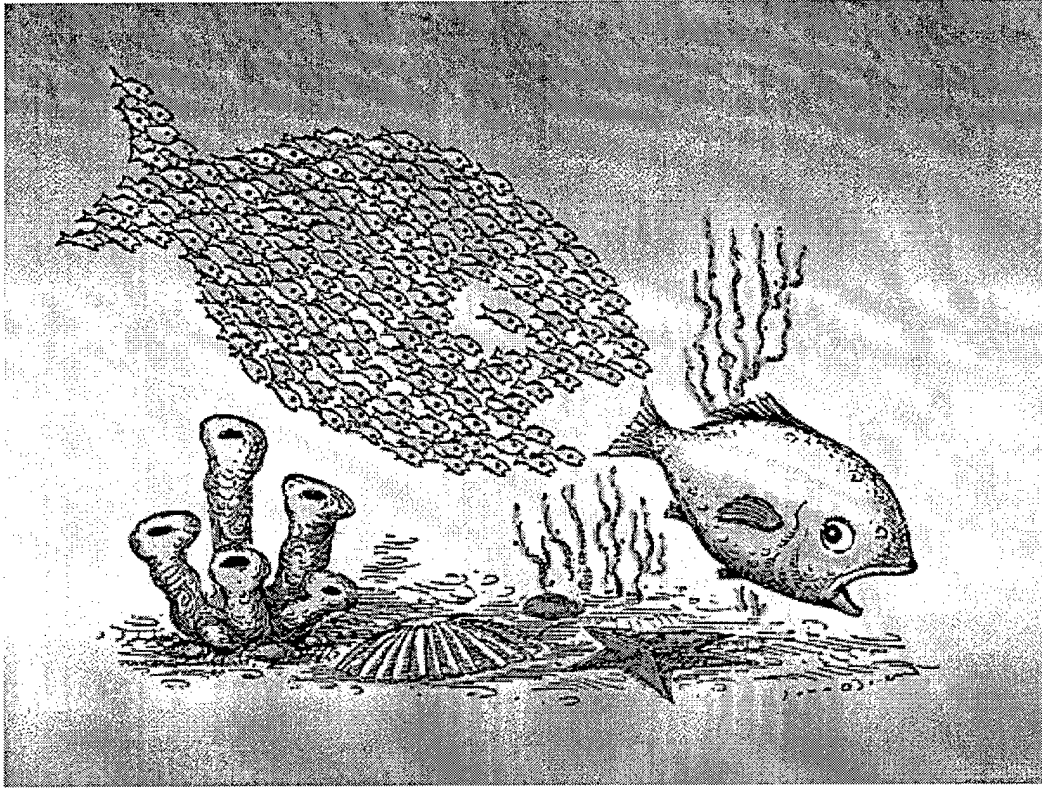


Figure 3. Concept of Emergence [Ilachinski 1997:p2]

actions change based on the local environment. The agents are autonomous in that they are independent and are not centrally controlled by a puppet master [Ilachinski 1997:p32]. These agent attributes drive the overall system characteristics.

A key characteristic of Complex Adaptive Systems is the concept of emergence or the appearance of higher level properties and behaviors that are neither found in nor are directly deducible from lower level properties. As depicted in Figure 3, emergence can be thought of as an un-scripted organizational level behavior resulting from the collective interaction of the elements in the organization. The organizational level behavior cannot be predicted by examining the individual parts separately [Jervis 1998:p3]. Emergence can also be conceptualized as air molecules which come together to form a tornado. The

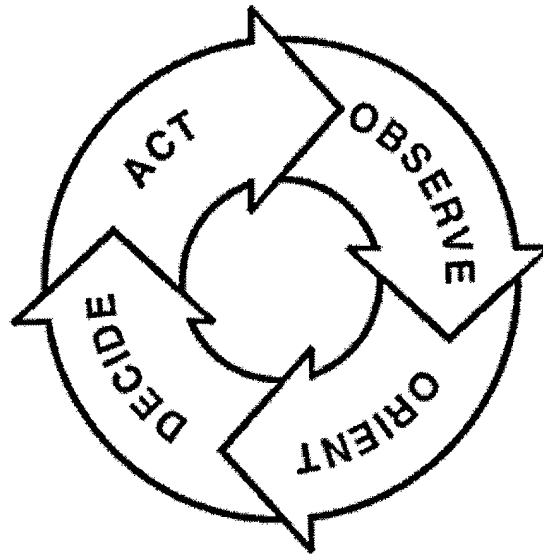


Figure 4. OODA Loop

resultant tornado cannot be deduced by examining the individual air molecules [Ilachinski 1997:p26].

One approach to implementing Complex Adaptive Systems is through agent-based modeling. This modeling technique embeds decision models in system elements allowing for adaptive decision making [Palmore 1999:p5]. This allows the individual elements, or agents, to act autonomously, governed only by an internal set of desires or drivers. Individual decision models also allow agent interaction to be governed by the agents themselves versus being governed by the system. Thus, individual decision models are key to Complex Adaptive Systems.

A widely recognized decision model is Col John Boyd's Observe, Orient, Decide, and Act Loop, or OODA Loop (Figure 4). The observe portion of the loop can be thought of as gathering intelligence information. The orient portion determines which information is of greatest value and how it is to be used in decision making. Based on the

information, a decision is made and finally, selected actions are executed before the cycle starts again. Boyd's theory suggests air strikes could,

...enmesh the enemy in a world of uncertainty, doubt, mistrust, confusion, disorder, fear, panic, chaos, and fold him back inside himself so that he can not cope with events as they unfold. [SOS 1998: p4245R3]

He felt the objective was to complete one's own OODA cycles faster than the adversary completes theirs. This could be accomplished by destroying the enemy's capability to observe, process, and act on information while preserving one's own ability to do so. After achieving a faster OODA Loop, one can interrupt the enemy's strategy and put them in a position of constantly having to react.

Adaptability is a key aspect of Boyd's theory. In fact, the Marine Corps propose adding another "A" to the end of OODA to stand for adapt [Upton 1998:p6]. The concept of adaptability on the battlefield is not a new one. In the 4th Century BC, in his book The Art of War, Sun Tzu [1991] stated, "So a military force has no constant formation, water has no constant shape; the ability to gain victory by changing and adapting according to the opponent is called genius." The OODA Loop captures the iterative nature of warfare. The OODA Loop theory recognizes that the result of one's actions are not just the direct effects on the adversary, but his adaptations and actions to our actions, which become inputs for our next cycle iteration [Beckerman 1999:p7]. Schmitt draws an analogy of this adaptation, or coping process to a kayaker paddling down a river:

Is a kayaker paddling down a raging river really in control of the situation? Does he control the river? Does he really even control his own course? Or does he try to steer his way between and around the rock formations which spell disaster as the rapids carry him along. For the

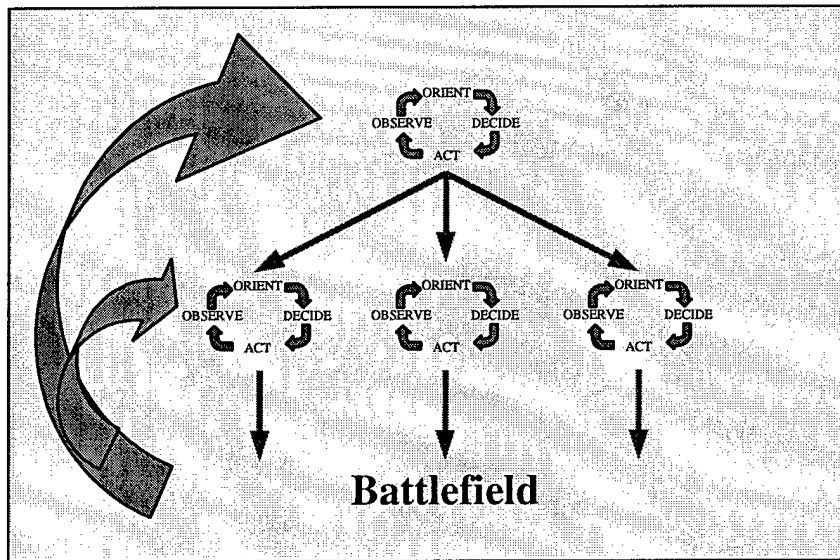


Figure 5. Hierarchically Linked OODA Loops [Beene 1998:p2-5]

kayaker, success—safely navigating the river—is not a matter of push-button precision. For the kayaker—as for the commander—it is a matter of coping with a changing, turbulent situation. Command in war is less the business of control than it is the business of coping. [Schmitt 1999:p9]

Beene [1998] developed a detailed treatment on levels of command and control and OODA Loops. Beene described a system of OODA Loops hierarchically and laterally connected. He envisioned OODA Loops at various levels of this hierarchy being dependent upon each other (Figure 5). Tighe extended Beene's analogy to an OODA web (Figure 6). Tighe's concept is based on each loop being inter-linked with loop size reflecting the OODA cycle length. His concept emphasizes that severing any loop degrades the overall strength and effectiveness of the web.

An alternative view, more in line with Complex Adaptive Systems, is a system of nested OODA Loops or an Emergent OODA Loop (Figure 7). The smallest loops, at the lowest levels, represent OODA Loops of physical entities. Higher level loops represent

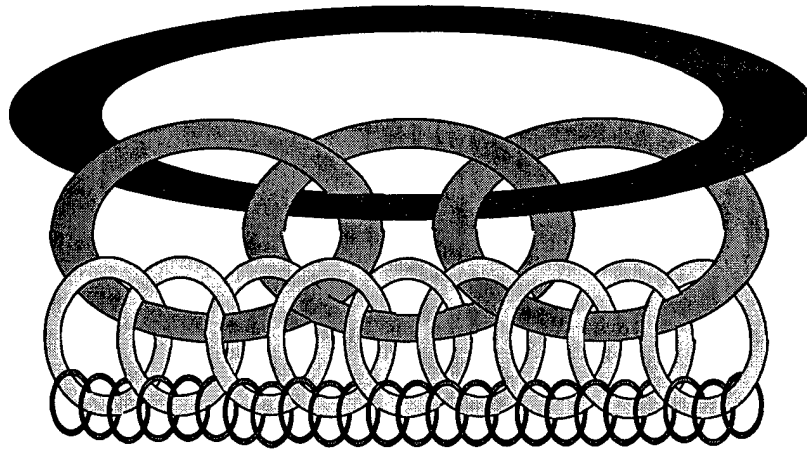


Figure 6. OODA Web [Tighe 1999:p20]

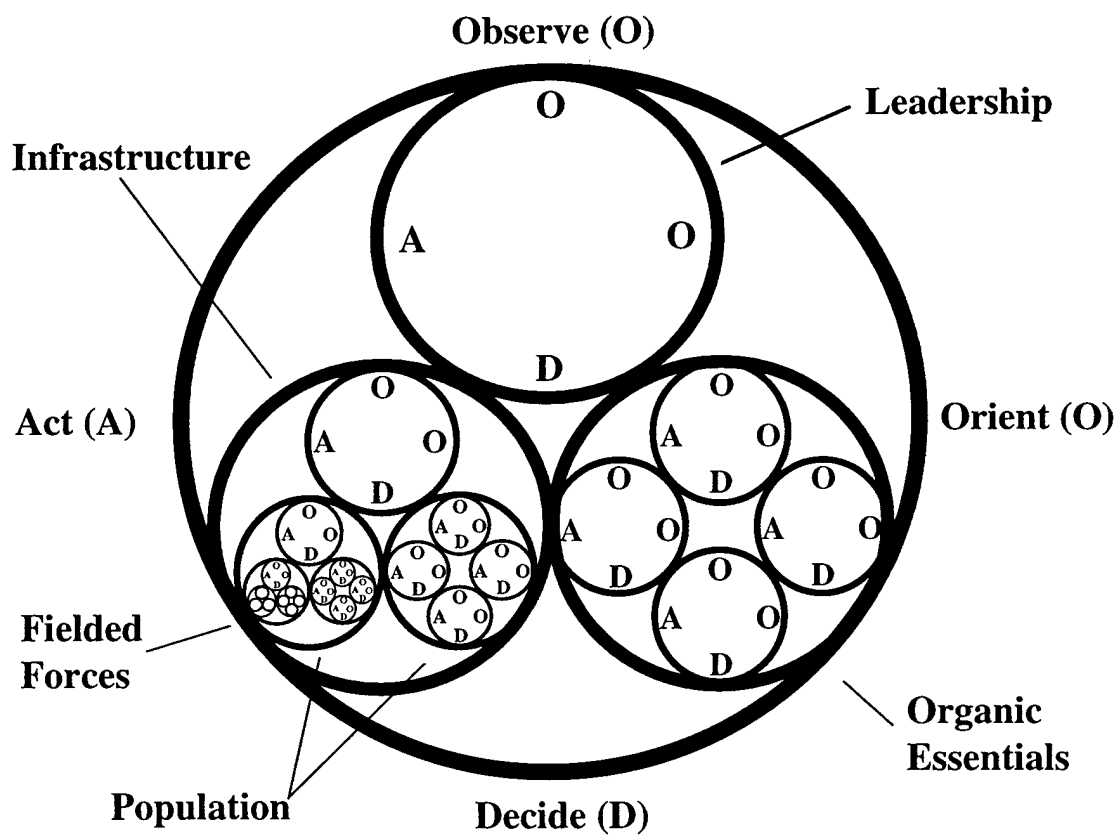


Figure 7. Emergent OODA Loop

organizational OODA Loops where individuals within the organization carry out functions related to observing, orienting, deciding, and acting. These higher levels of abstraction also represent emergent behaviors. The Emergent OODA Loop view also lends itself to incorporating Warden's concepts related to centers of gravity. Regardless of preferred conceptualization, the OODA Loop offers an ideal way to model the adaptive portion of a Complex Adaptive System.

But, is war a Complex Adaptive System? Schmitt [1999] suggests war is a Complex Adaptive System with matter, information, and energy being exchanged between open hierarchies. Schmitt feels war is in a constant state of flux and never at equilibrium. War is driven from equilibrium by influxes from the environment in the form of materiel and by leadership, political motive, training, and creative tactics. These flows are dampened by Clausewitz's friction through attrition of people and materiel as well as, fatigue, loss of morale, poor tactics, and uninspired leadership. These exchanges take place in a complex, hierarchical network of simultaneous, distributed linkages between various elements at various levels in each hierarchy resulting in feedback loops [Schmitt 1999:p5]. Ilachinski also views war as a complex adaptive system (Table 3).

Ilachinski has arguably initiated the use of agent-based modeling for military purposes. Sponsored by the Marine Corps, Ilachinski [1997] developed the Irreducible Semi-Autonomous Adaptive Combat (ISAAC) model based on the Complex Adaptive System concept. ISAAC simulates the interaction of fighting marines on the battlefield. In ISAAC, each marine is represented by an agent that acts and reacts based on the agent's surrounding environment. The driving factor for development of ISAAC was that existing models did not take into account the use of tactics involving maneuver and thus

Table 3. Warfare as a Complex Adaptive System [Ilachinski 1998:p74]

General Property of Complex System	Relevance to Warfare
Nonlinear Interaction	Combat forces composed of a large number of non-linearly interacting parts; sources include feedback loops in C2 hierarchy, interpretation and adaptation to enemy actions, decision making processes, and elements of chance
Nonreductionist	The fighting ability of a combat force cannot be understood as a simple aggregate function of the fighting ability of individual combatants
Emergent Behavior	The global patterns of behavior on the combat battlefield unfold, or emerge out of nested sequences of local interaction rules and doctrine
Hierarchical Structure	Combat forces are typically organized in a command and control like hierarchy
Decentralized Control	There is no master oracle (i.e. puppet master) dictating the actions of each and every combatant; the course of a battle is ultimately dictated by local decisions made by each combatant
Self-Organization	Local action, which often appears chaotic, includes long range order
Non-equilibrium Order	Military conflicts by their nature proceed far from equilibrium; understanding how combat unfolds is more important than knowing the end state
Adaptation	In order to survive, combat forces must continually adapt to a changing environment, and continually look for better ways of adapting to the behavior pattern of the enemy
Collectivist Dynamics	There is continual feedback between the behavior of low level combatants and the high level command structure

did not capture the way marines fight [Ilachinski 1997:piii].

Tighe [1999] extended the ISAAC concept in an effort to capture what airpower brings to the fight in terms of strategic effects. He used a Complex Adaptive System approach providing each agent with an OODA Loop in order to investigate the effect of improved decision cycle times. He found agents with shorter decision cycles had a decisive, nonlinear advantage over their adversaries. This nonlinear advantage coincides with what Air Force doctrine expects from a strategic attack. Although simple in scope,

Tighe's model suggests that Complex Adaptive System models offer a feasible approach to modeling strategic effects and that OODA Loops are an effective way to gauge strategic effects [Tighe 1999:p67].

Earlier it was suggested that unpredictability in war was the result of interaction among animate entities that act, react, and preempt one another. Complex Adaptive Systems and OODA Loop theory provide a methodology to examine and gain insight into the nature of these interactions. Building on the work of Ilachinski and Tighe, a Hierarchical Interactive Theater Model (HITM) was constructed.

3. Hierarchical Interactive Theater Model (HITM)

But in war, more than in any other subject, we must begin by looking at the nature of the whole; for here more than elsewhere, the part and the whole must always be thought of together.

-- Carl von Clausewitz

3.1 HITM Background & Overview

Tighe [1999] developed a simulation model to examine OODA Loop advantage. The purpose of the OODA Loop Advantage Model was to investigate whether OODA length differences produce the nonlinear advantages predicted by Air Force doctrine resulting from strategic attack. Tighe's proof-of-concept model is a Complex Adaptive System made up of adaptive agents. These agents are individual combatants with a constant OODA Loop processing time. One aspect of the OODA Loop Advantage Model, which makes it different from other models of Complex Adaptive Systems, is the use of multithreading. Most models of Complex Adaptive Systems consist of agent decision cycles that occur at uniform time intervals controlled by a master simulation clock. Multithreading, on-the-other-hand, gives each agent autonomy and freedom from main program control [Tighe 1999:p43].

Tighe's OODA Loop Advantage Model is a two-sided (Red and Blue) battlespace with combatants defending their own base. Figure 8 depicts the start of the simulation with blue in the upper left corner and red is in the lower right corner. As the simulation progresses, each combatant moves through its OODA cycle deciding whether to attack, regroup, or continue towards the enemy base (Figure 9). Various aspects of the model

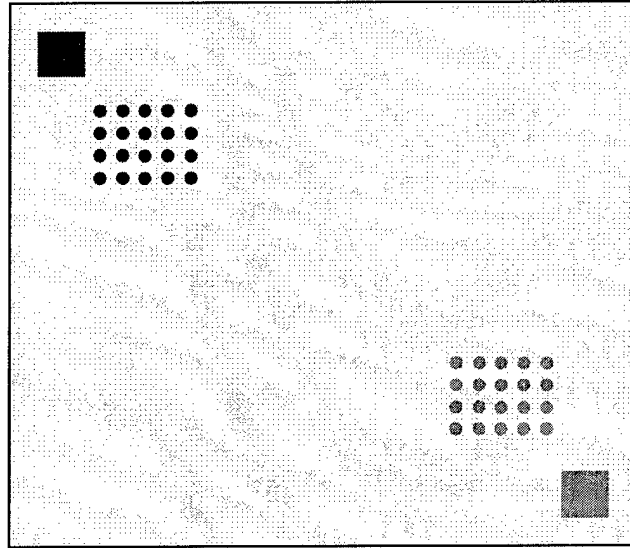


Figure 8. OODA Loop Advantage Model [Tighe 1999:p44]

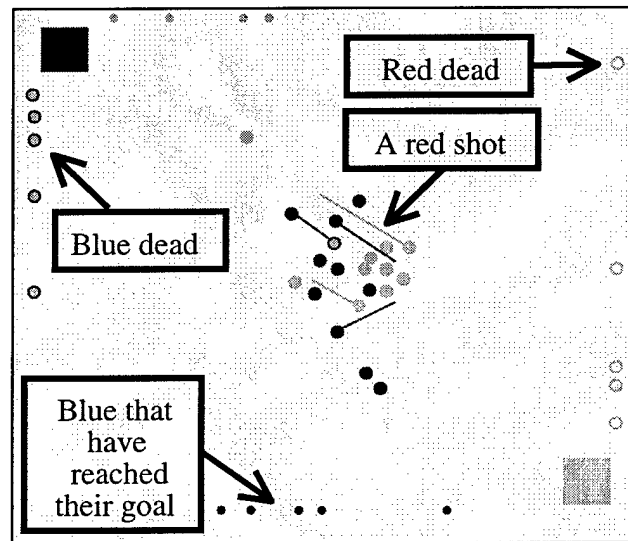


Figure 9. OODA Loop Advantage Simulation [Tighe 1999:p44]

can be manipulated between simulation runs, such as force size and OODA Loop cycle time, in order to conduct experiments to explore OODA Loop advantage. HITM is constructed in a similar manner. While Tighe's model suggests an agent-based model as a viable alternative to classical Lanchester methods for capturing strategic effects, it is

limited in scope. A natural extension, embodied in HITM, is to expand to a more complicated system.

The purpose of HITM is to examine the relationship between strategic effects and OODA Loops. HITM models a conflict between two equally matched military forces. Each side has identical military chains-of-command, force structure, and force strength, however, the opponents have opposed objectives. Autonomous agents, each with its own OODA Loop, form the ranks at each level of the chains-of-command. Agents have actions which they can carry out in support of overall objectives. Agents at each level react to the enemy so enemy actions impact individual agent decisions. Each side also has resources, which are considered targets by the adversary. Agents require these resources to carry out their actions. The simulation endgame occurs when one opponent achieves its objective, which is to capture the adversary's airbase. Key enhancements in HITM over the OODA Loop Advantage Model are dynamic OODA Loop times and multiple classes of agents. HITM also contains a number of targets that populate the battlespace.

3.2 HITM Battlespace

The battlespace depicted in HITM consists of two equally sized areas (Figure 10). The areas represent each opponent's territory. The entire battlespace is considered flat terrain, implying geography is not important. Each opponent's territory contains resources representing war materials and processes. Both opponents have an equal amount of resources, all of which can be targeted by the adversary. The resources are positioned in a similar layout for each opponent, negating any geographic advantage.

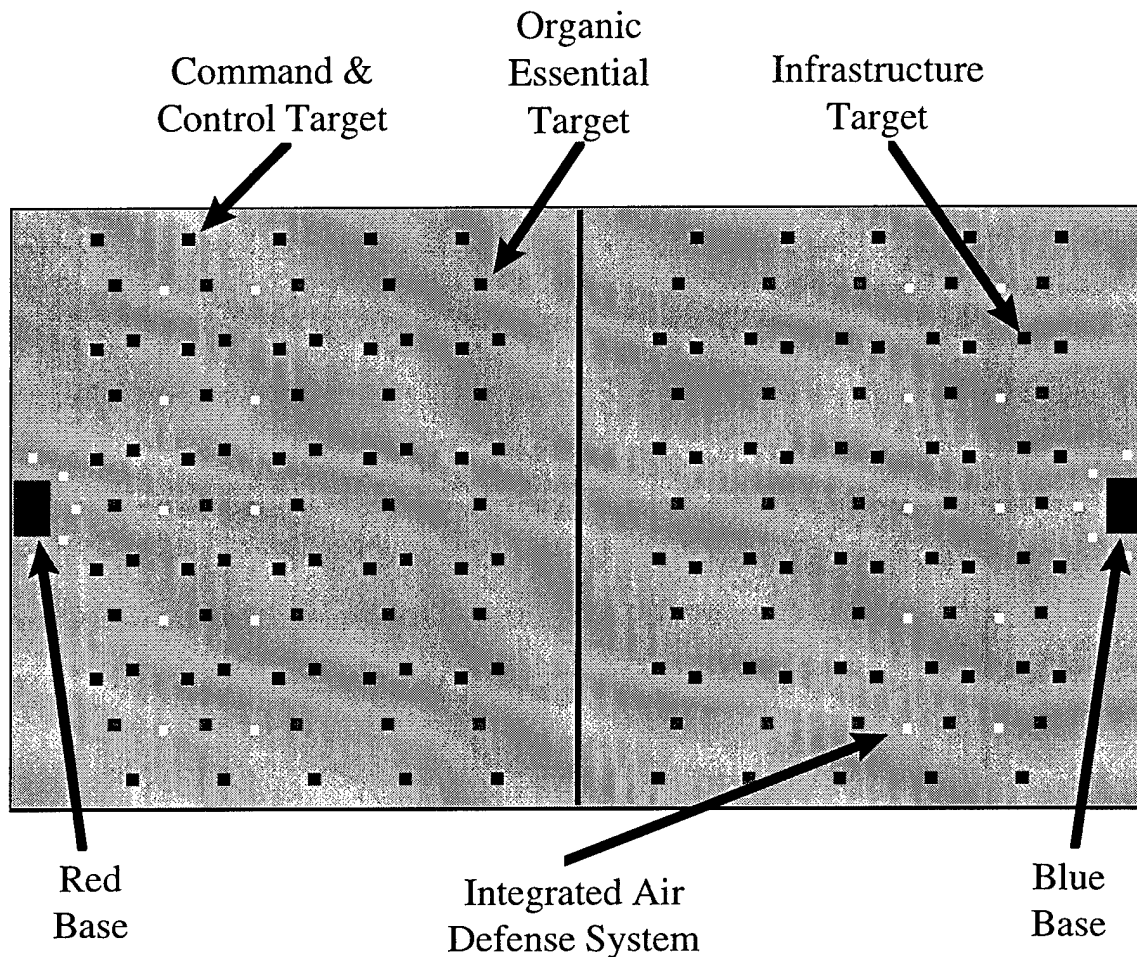


Figure 10. HITM Battlespace

There are three primary target sets derived from Warden's five rings (Figure 2) and include leadership/command and control (C2), organic essentials, and infrastructure. The C2 targets represent intelligence gathering resources and communication links to include satellite down-links, radar sites, and telecommunications nodes. A strike against these targets degrades ability to gather intelligence and communicate. The organic essential targets represent sources of petroleum and other fuel products to include fuel storage depots, petroleum refining operations, as well as petroleum pipelines. A strike against these targets impacts rate of delivery and overall availability of fuel. The

infrastructure targets include roads, bridges, and ammunition/weapon storage facilities. A strike against these targets impacts rate of delivery and overall availability of ammunition/weapons.

The three primary target sets are assumed to be highly redundant networks. This implies a single strike cannot eliminate a linkage between two points, but a single strike will cause degradation across the entire network. In addition, resources deeper in an opponents territory have more significance. For example, a single organic essential resource deep in an opponents territory contributes over 5% of fuel resources, however, an organic essential resource near the border between the two opponents, only represents 1%. The deep resources are also considered higher value targets for the adversary.

An additional fourth target set in HITM, related to Warden's rings, is fielded forces. Each opponent is limited to using 48 multipurpose aircraft at once. These aircraft have similar capabilities to the F-16 Falcon (Figure 11). As aircraft are destroyed, HITM assumes additional aircraft resources can be obtained from other theaters. However, the rate at which these additional aircraft are delivered depends on leadership/command and control resources available, as well as the total number of aircraft lost.

Each opponent also has 65 ground units. The units represent elements of a single mechanized infantry division to include tanks, armored vehicles, and multiple launch rocket systems. However, ground forces do not have attack helicopters and rockets can only be used against aircraft during Close Air Support (CAS) attacks. Unlike the aircraft, ground units are not replenished.

Each side has an airbase where aircraft are launched. The base cannot be completely destroyed, however, direct strikes against the base result in increased

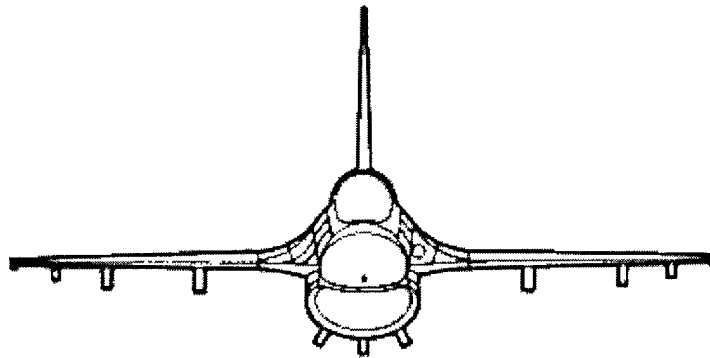


Figure 11. F-16 Fighting Falcon [Three-Four-Nine 1999]

turnaround time for aircraft as airbase attacks represent strikes against runways and hangar facilities.

The final resource/target modeled for each opponent is an Integrated Air Defense System (IADS). This system is composed of surface-to-air missile (SAM) sites linked with radar facilities. The IADS is highly dependent on both leadership/command and control and infrastructure resources. The range of the IADS sensors are tied to leadership/command and control resources available and IADS probability of kill is linked to infrastructure resources available.

The battlespace is modeled so the opponents are equally matched. Interaction between the agents tip the balance. The following section describes these interactions.

3.3 Agents

A key characteristic of Complex Adaptive Systems is a large number of non-homogeneous agents. In HITM, there are five classes of agents that make up each opponent's chain-of-command to include Commander, Operations, Ground Units,

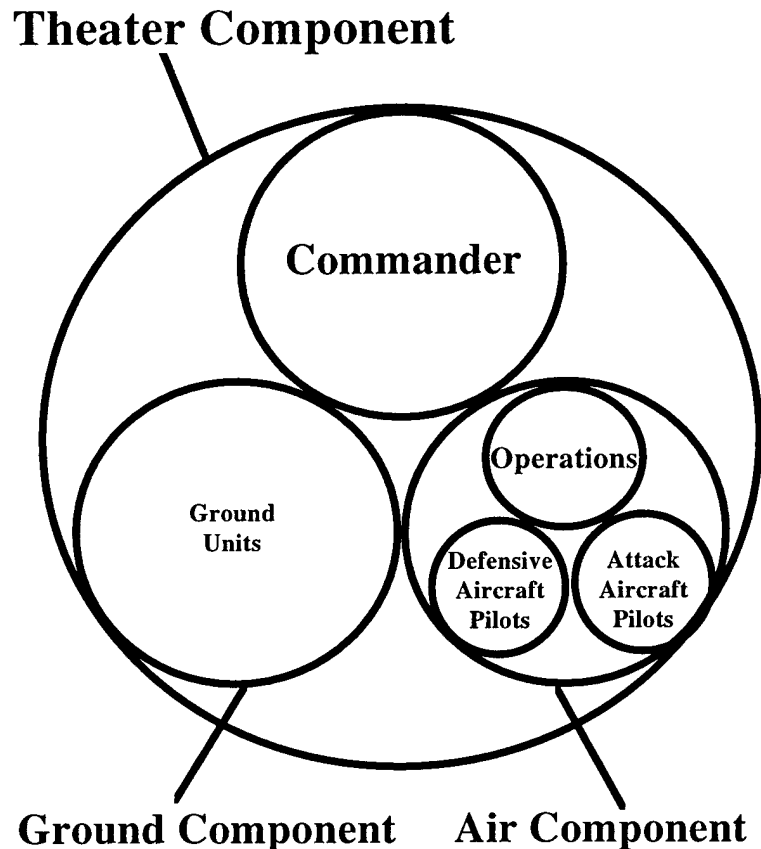


Figure 12. HITM Chain-of-Command

Defensive Aircraft Pilots, and Attack Aircraft Pilots. Figure 12 shows these different classes of agents.

Agents within the same class have unique characteristics such as experience and unit cohesion, so no two agents are exactly alike. In addition, agents following the same decision path, may take different amounts of time to complete the same tasks. This is accomplished by running each agent as a separate thread of execution or mini-program.

All agents follow the same generic decision cycle (Figure 13). However, the various agents take different amounts of time to complete their process. For example, the Commander's decision process is approximately 10 times that of the ground units at the

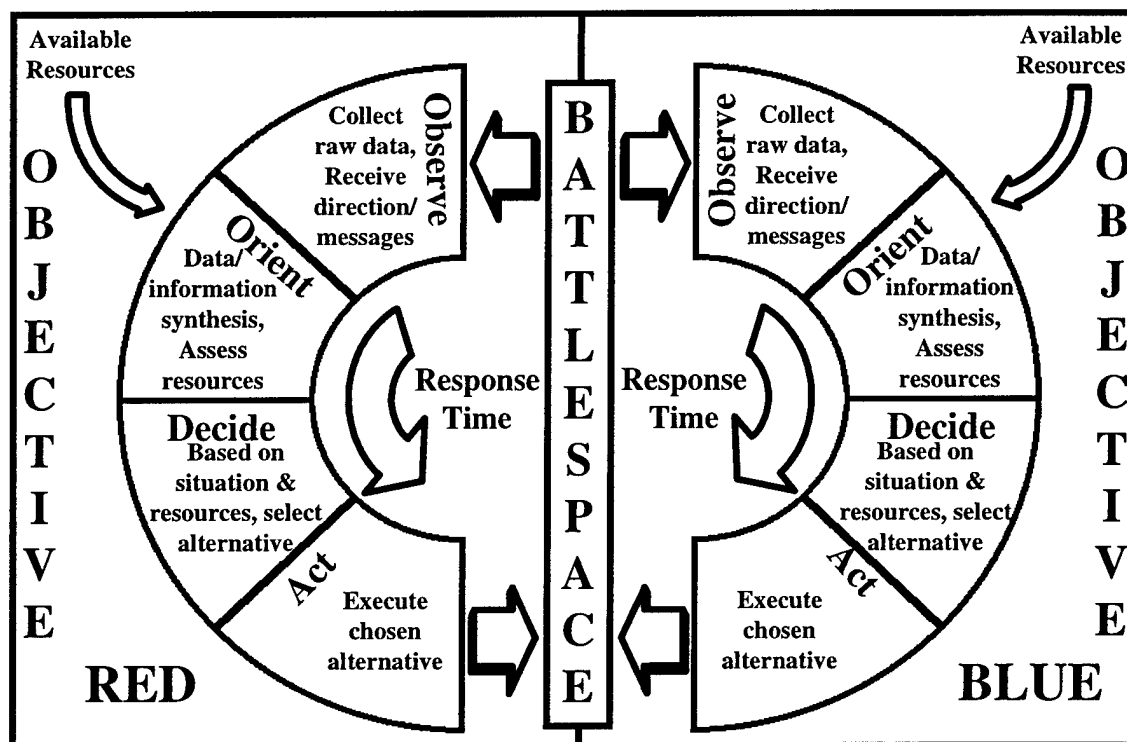


Figure 13. Generic Agent OODA Loop

start of the simulation. The decision process response time changes as the simulation progresses.

Agents begin each decision cycle by observing. In the observe phase, the agents take in raw data, as well as direction/messages from other agents. In the next phase, orient, agents synthesize the raw data from the observe phase into information. Also during the orient phase, agents determine their available resources. Knowing the situation and the resources available, the agents move into the decide phase. In this phase, the agents select from a number of alternatives based on the results of the orient phase. The final phase is act. In this phase, the agents execute their chosen alternative.

All agents continue to repeat their decision cycle until one opponent achieves its objective of capturing the other opponent's airbase. The speed at which an agent moves

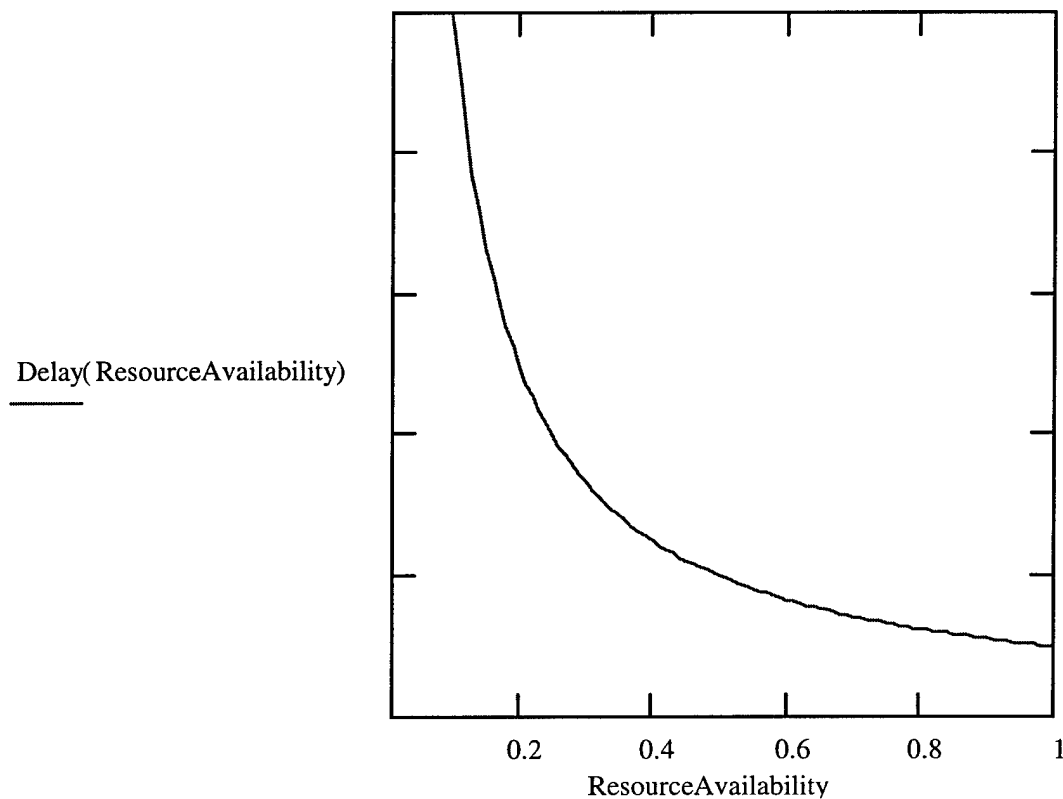


Figure 14. Decision Cycle Time Degradation Curve

through its decision cycle is driven by external factors such as resources available as well as internal factors such as unit cohesion. Resource availability, however, has the largest impact. The relative impact for all agents is described by the curve in Figure 14. The curve emphasizes that as resources become more scarce, decision cycle time degradation accelerates.

HITM also incorporates battlespace uncertainty. The uncertainty is added by returning intelligence data to the agents that may be different from the actual values. In addition, the decision cycle delay incorporates the impact of acting on old information.

These general details apply to all agents. Specific details on the decision processes for each agent class are outlined in the following sections.

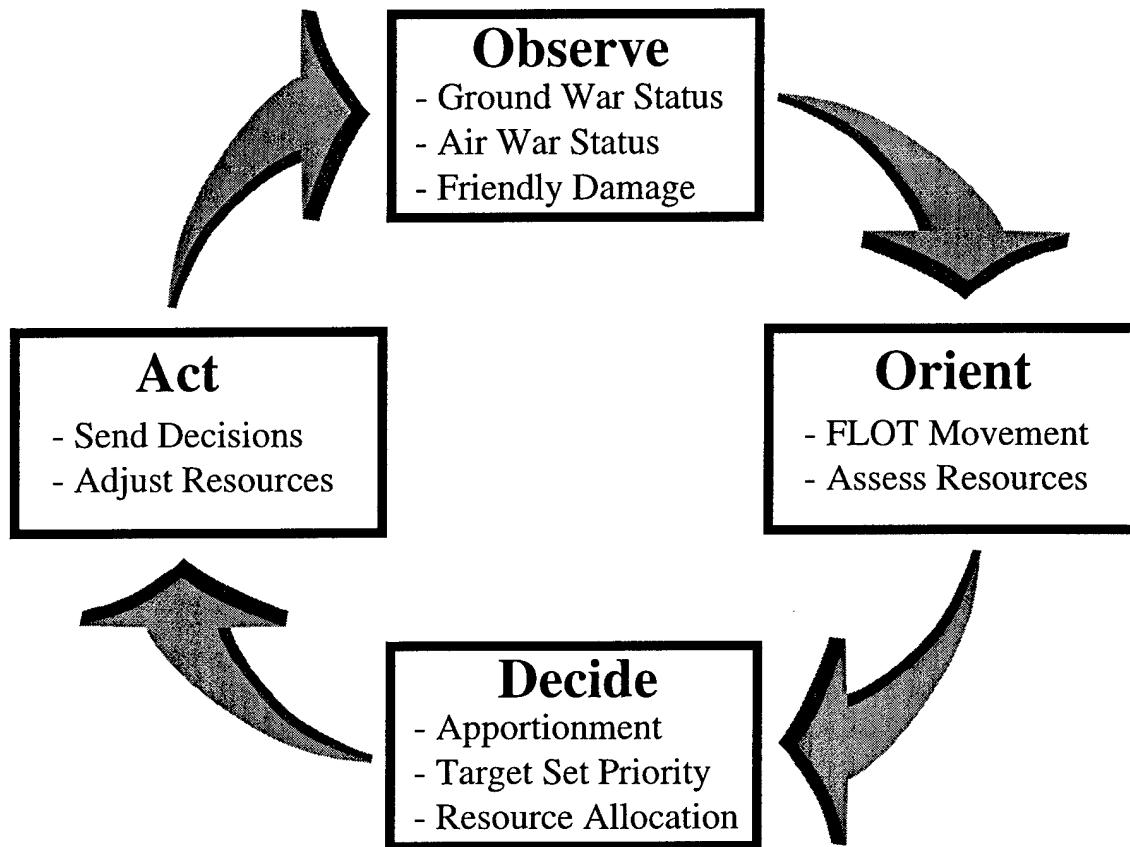


Figure 15. Commander's Decision Cycle

3.3.1 Commander

The Commander's objective in HITM is to ensure proper coordination of ground and air efforts to attain the overall objective. The decision process used by the Commander is depicted in Figure 15. The Commander's decision cycle begins with the observe phase. This phase involves the collection of intelligence such as data on the status of the ground war to include ground unit wins, Forward Line Of Troops (FLOT) location, and distance between enemy ground units. In addition, the intelligence includes information on friendly resources including aircraft lost. In the next phase, orient, the raw data is synthesized into information on which to base decisions. The time to collect

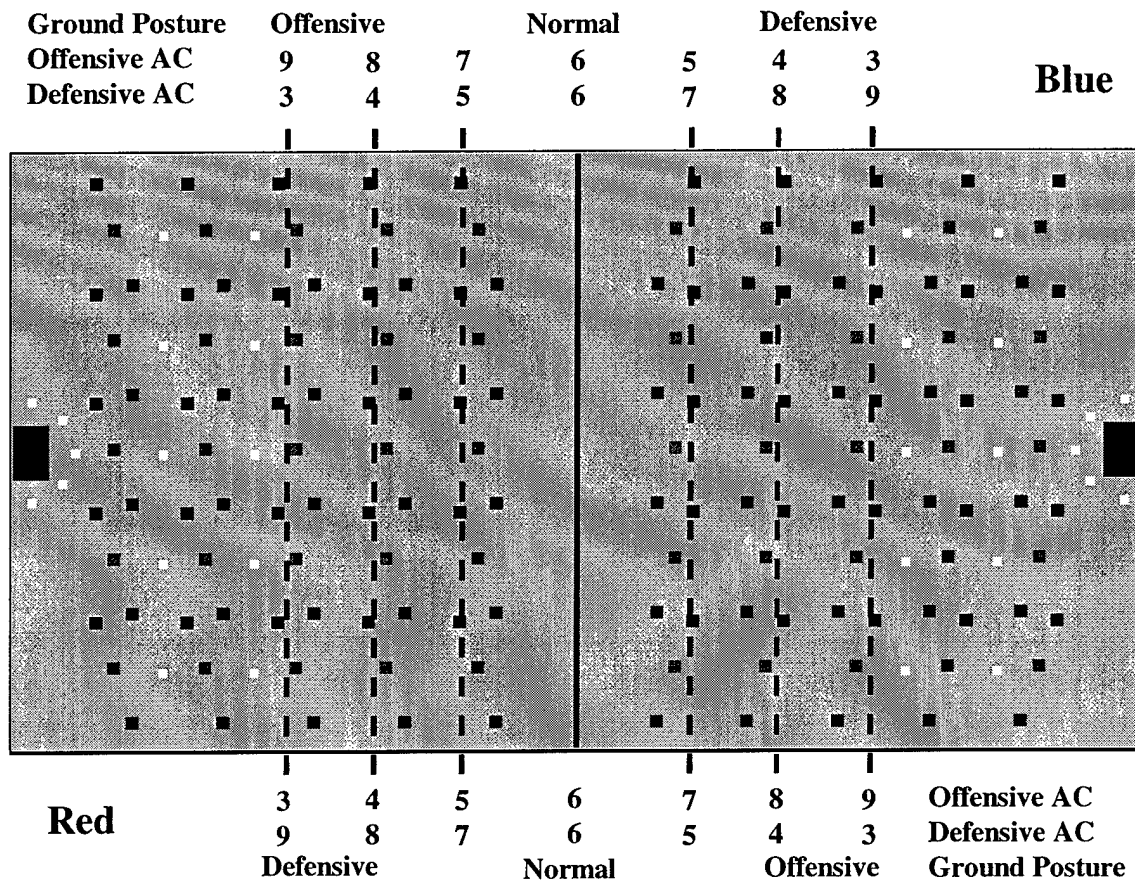


Figure 16. Commander Decision Criteria

and synthesize this information is a function of C2 resources available. In the next phase, decide, the Commander uses the information from the orient phase to make decisions.

The first decisions relate to aircraft apportionment and ground unit posture.

Figure 16 shows the number of aircraft to be used in offensive and defensive roles based on FLOT location. In addition, the figure shows the decision criteria for ground force posture. There are three ground force postures: defensive, normal, and offensive. In the defensive posture, ground units cannot advance unless they are within communications distance of two other units. In normal posture, ground units only need to be within communications distance of one other unit in order to advance. In an offensive posture,

each unit can advance without being in communications range of other units. For example, if red was approximately half way into blue's territory, blue would go to a defensive ground posture and allocate three 4-ship formations to offensive operations and nine 4-ship formations to defensive operations. Red on-the-other-hand, would go to a offensive ground posture and allocate nine 4-ship formations to offensive operations and three 4-ship formations to defensive operations.

The Commander determines target set priorities based on ground war intelligence. If the enemy has won more on the ground since the last intelligence report, then infrastructure is targeted. If the enemy has advanced more than a specified amount since the last intelligence report, then organic essentials are targeted. If enemy ground unit spacing has increased since the last intelligence report, then C2 is targeted. Only one target set can be selected by the Commander per decision cycle. If more than one condition is true, the targets have the following default priorities: C2, organic essentials, and infrastructure. Once these decisions are made, the apportionment and target set priority decisions are communicated to Operations and the ground force posture decision is communicated to the ground units. The delay to communicate the direction is based on C2 resources available.

Every decision cycle, the Commander has the opportunity to rebuild destroyed capabilities. The most degraded capability among C2, organic essentials, and infrastructure is always chosen to be bolstered. In addition, the highest value resource, on the friendly side of the FLOT, within the chosen resource set is rebuilt. The delay to rebuild a resource is a function of all other available resources. In addition, every decision cycle, the Commander has the opportunity to strengthen air assets. This is only

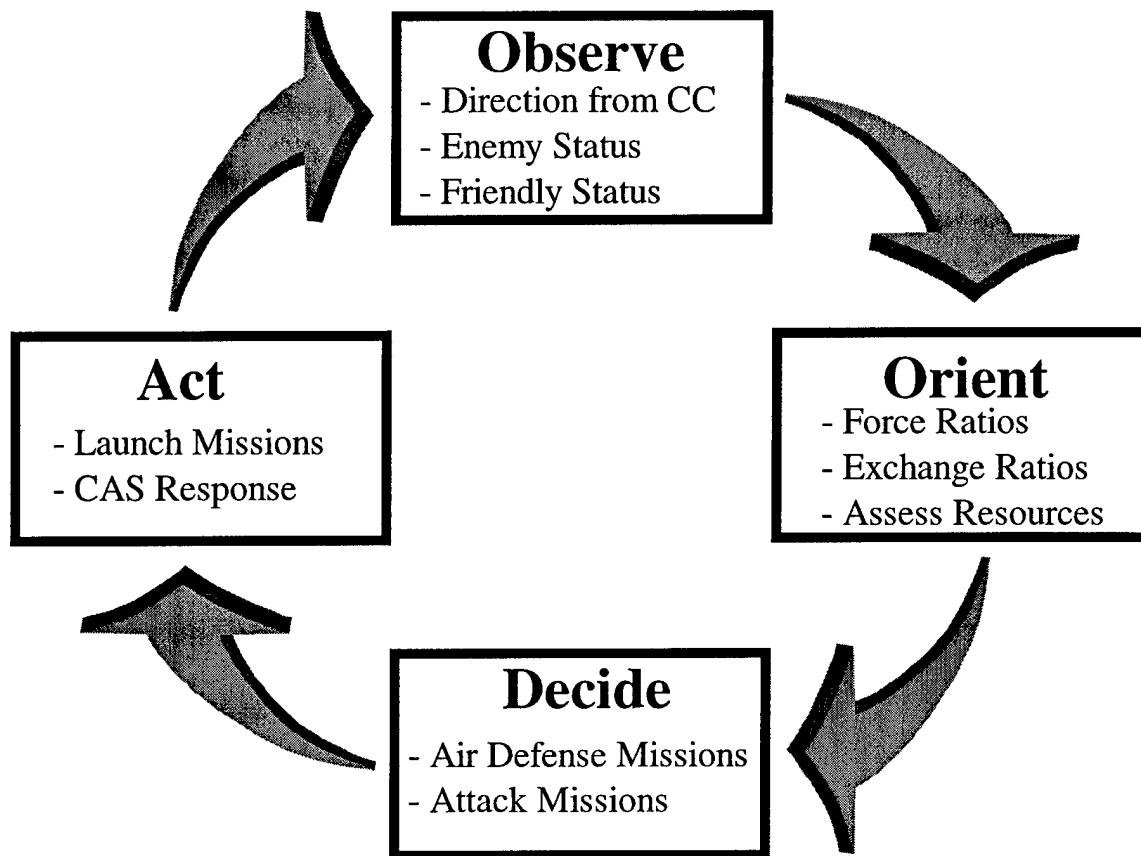


Figure 17. Decision Cycle for Operations

attempted if the number of friendly aircraft lost, since the last intelligence report, is greater than the number of enemy aircraft lost. The delay to strengthen the aircraft fleet is based on all available resources. The primary need for the aircraft lies with Operations.

3.3.2 Operations

The objective of Operations is to direct air efforts in support of the Commander's objective. The decision process for Operations is depicted in Figure 17. Operations begins its decision cycle in the observe phase by receiving direction from the Commander concerning apportionment and target set priority. Also in this phase, Operations collects intelligence on the ground war, enemy targets, enemy air assets, friendly air assets, and

resources available. In the next phase, orient, Operations synthesizes the data from the observe phase into information on which to base decisions. Operations uses the information from the orient phase to make the decisions in the next phase, decide.

The first decision Operations makes concerns air defense. If aircraft are available, Operations will launch in accordance with the Commander's apportionment decision. The pilots are given three way points to fly over which Operations chooses based on FLOT intelligence. The chosen points are aimed at leading attack missions and protecting friendly resources.

The next decision made by Operations is whether to launch an attack mission and if so, which target to strike. If attack aircraft are available, Operations will launch in accordance with the Commander's apportionment decision. The target decision is based on the Commander's target set priority, but the specific target is determined by Operations. The specific target chosen depends on the intelligence received concerning enemy and friendly air assets. If friendly defensive aircraft outnumber enemy defensive aircraft and friendly attack aircraft outnumber enemy attack aircraft, either a high value target, IADS site, or the enemy airbase is targeted. If friendly defensive aircraft outnumber enemy defensive aircraft or friendly attack aircraft outnumber enemy attack aircraft, either a medium value target, IADS site, or the airbase is targeted. These conditions represent Operations standard operating procedure and the second condition will not override the first. However, if neither of the conditions are met, Operations can choose from any target within the target set designated by the Commander. This mechanism allows Operations to take risks. Regardless of target set priority or target selected, if Operations receives a Close Air Support (CAS) request from a ground unit,

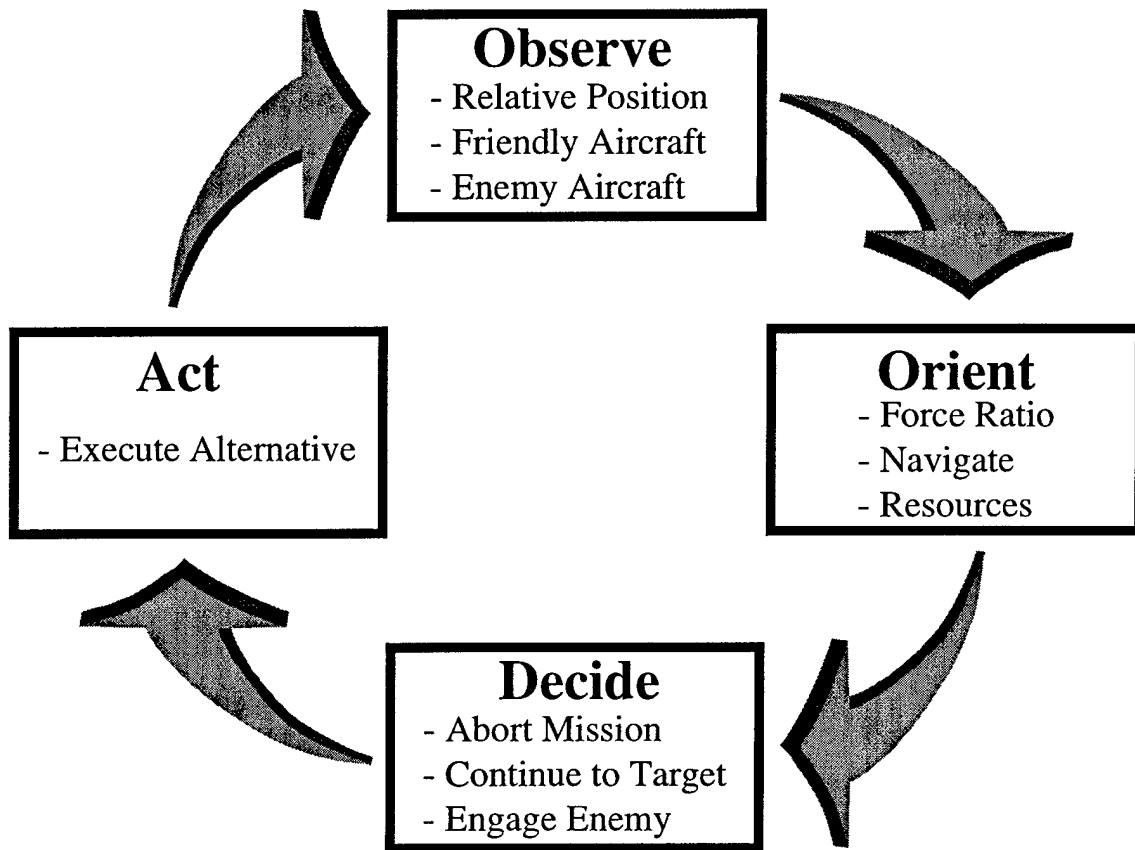


Figure 18. Attack Pilot Decision Cycle

the request overrides all other attack mission priorities. Using these criteria for decision making, Operations enters the last phase, act, where the chosen alternative is executed.

All aircraft are launched as 4-ship formations. The time to launch the 4-ship is a function of all resources available, the total number of friendly aircraft lost, and the number of successful airbase attacks carried out by the enemy. Operations is empowered to launch the defensive aircraft at anytime, however, the Commander has to send a target set priority before an attack aircraft can be launched.

3.3.3 Attack Aircraft Pilot

The objective of the attack pilot is to destroy targets, either ground forces or enemy resources, designated by Operations. Each pilot in HITM is unique. Each has a different experience level and a different level of will which are initialized randomly. These characteristics impact execution of the pilot's mission. The decision process for the attack pilots, as they proceed to their objective, is depicted in Figure 18.

The attack pilot decision process begins in the observe phase by collecting intelligence. For the attack pilot, this involves determining current position relative to the target for navigation. It also includes determining the number of friendly and enemy aircraft within sensor range. In the next phase, orient, the pilot determines if the ratio of detected enemy to friendly aircraft exceeds the pilot's will to continue the mission. If this condition is true, the pilot may choose to abort the mission in the decide phase. In the final phase, act, the pilot executes the chosen alternative. When a mission is aborted the pilot navigates back to base. However, as long as the pilot does not abort the mission, the pilot continues to the target even if enemy aircraft are in sensor range. The attack pilot will only engage enemy aircraft if the enemy is within firing range. When the attack pilot engages an enemy aircraft, the probability of kill is based on pilot experience, level of communications, and ammunition.

Each opponent has an IADS. As noted earlier, the IADS is composed of a number of SAM sites and radar facilities with the effectiveness of the system being based on C2 and infrastructure resources. A pilot has no warning before entry into a SAM site's range. Once inside the site's range, the pilot can engage the site. HITM plays the IADS and the pilot as equally matched with one side scoring the kill.

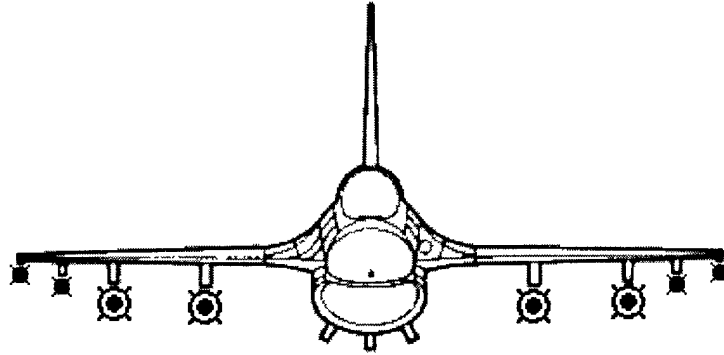


Figure 19. HITM Attack Aircraft [Three-Four-Nine 1999]

On CAS missions, assuming the pilot made it to target, the pilot has a 95% chance of successfully attacking the ground unit. However, ground units can return fire and potentially destroy the aircraft. The effectiveness of the ground units against aircraft is a function of pilot experience and ground unit cohesion. If the ground unit's cohesion factor is greater than the pilot's experience factor the aircraft is shot down.

If a pilot makes it to the designated target, the pilot has a 95% chance of successfully destroying the target. HITM assumes the F-16-like attack aircraft (Figure 19) are equipped with precision guided air-to-surface weapons such as the AGM-65 Maverick infra-red guided missile. These missiles are typically used for CAS missions but are also effective in Suppression of Enemy Air Defenses (SEAD) and interdiction missions. HITM assumes multiple missiles are effective against C2, organic essential, and infrastructure targets within the HITM battlespace. For air-to-air engagements, the attack aircraft are equipped with a weapon such as the AIM-120 fire-and-forget AMRAAM (Advanced Medium Range Air-to-Air Missile). The HITM defensive aircraft have similar capabilities.

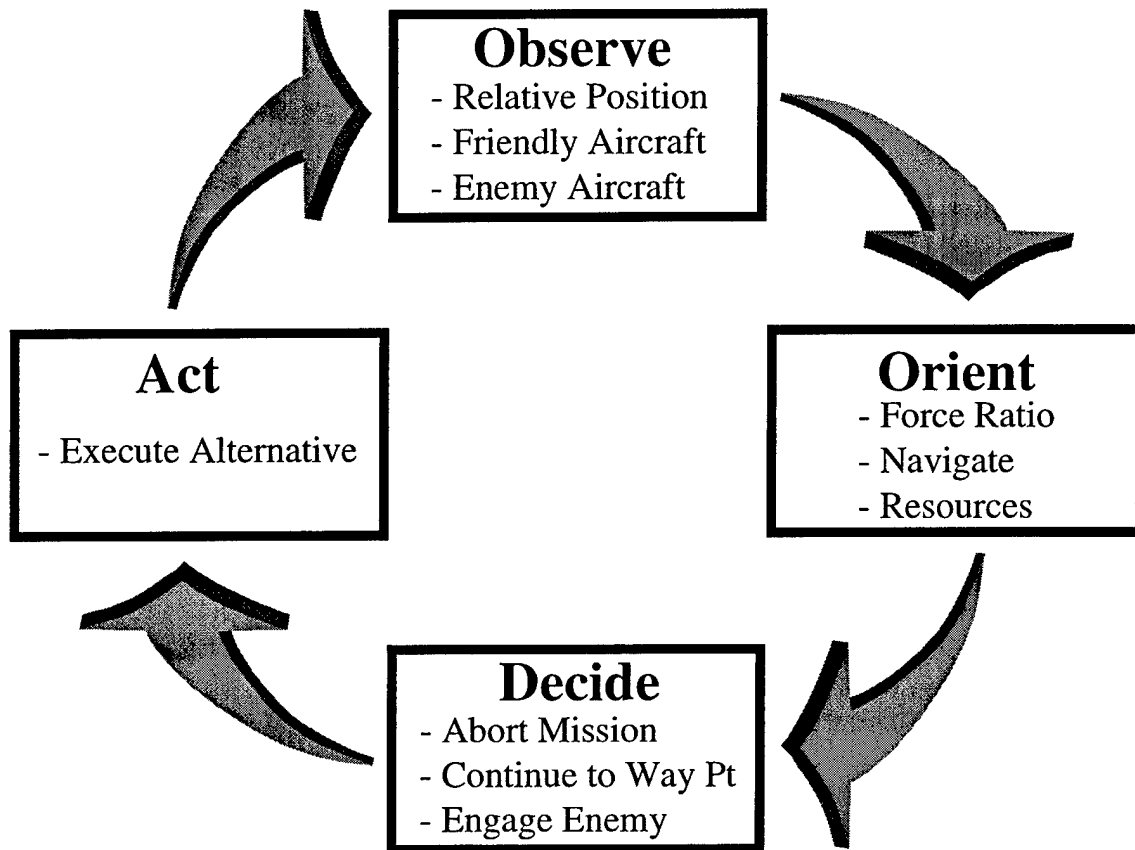


Figure 20. Defense Pilot Decision Cycle

3.3.4 Defensive Aircraft Pilot

The objective for the defensive aircraft pilot is to obtain/maintain air superiority in the airspace assigned by Operations. Similar to the attack pilots, each pilot is unique, with a different experience and will level. The decision process for the defensive aircraft pilots is depicted in Figure 20.

The pilot decision process begins in the observe phase with collecting intelligence. This involves determining current position relative to the target for navigation. It also includes assessing the number of friendly and enemy aircraft within sensor range. In the next phase, orient, the pilot determines if the ratio of detected enemy

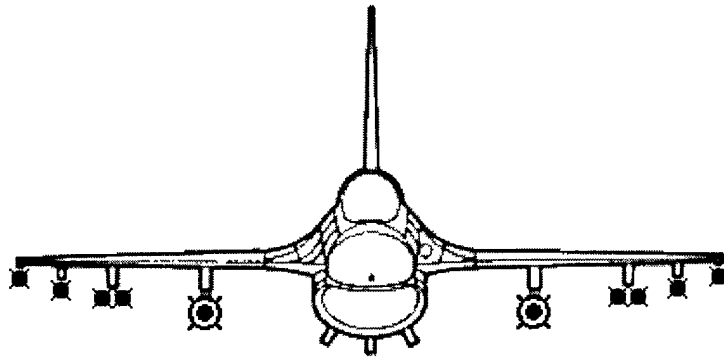


Figure 21. HITM Defensive Aircraft [Three-Four-Nine 1999]

to friendly aircraft exceeds the pilot's will to continue. If this condition is true, the pilot can choose to abort the mission in the decide phase. In the final phase, act, the pilot executes the chosen alternative.

When a mission is aborted, the pilot navigates back to base. As long as the pilot does not abort the mission, the pilot continues to the next assigned way point. However, unlike the attack pilot, the defensive aircraft pilot will deviate from course to intercept any enemy aircraft within sensor range. When the defensive aircraft pilot engages an enemy aircraft, the probability of kill is based on pilot experience, level of communications, and ammunition.

As described for the attack pilot, each opponent has an IADS composed of SAM sites and radar facilities. The effectiveness of the system is based on the enemy's C2 and infrastructure resources. The IADS range is proportional to enemy C2 resources available and the IADS probability of kill is proportional to enemy infrastructure resources available. A pilot has no warning before entering a SAM site's range. HITM plays the IADS and the pilot as equally matched with one side scoring the kill.

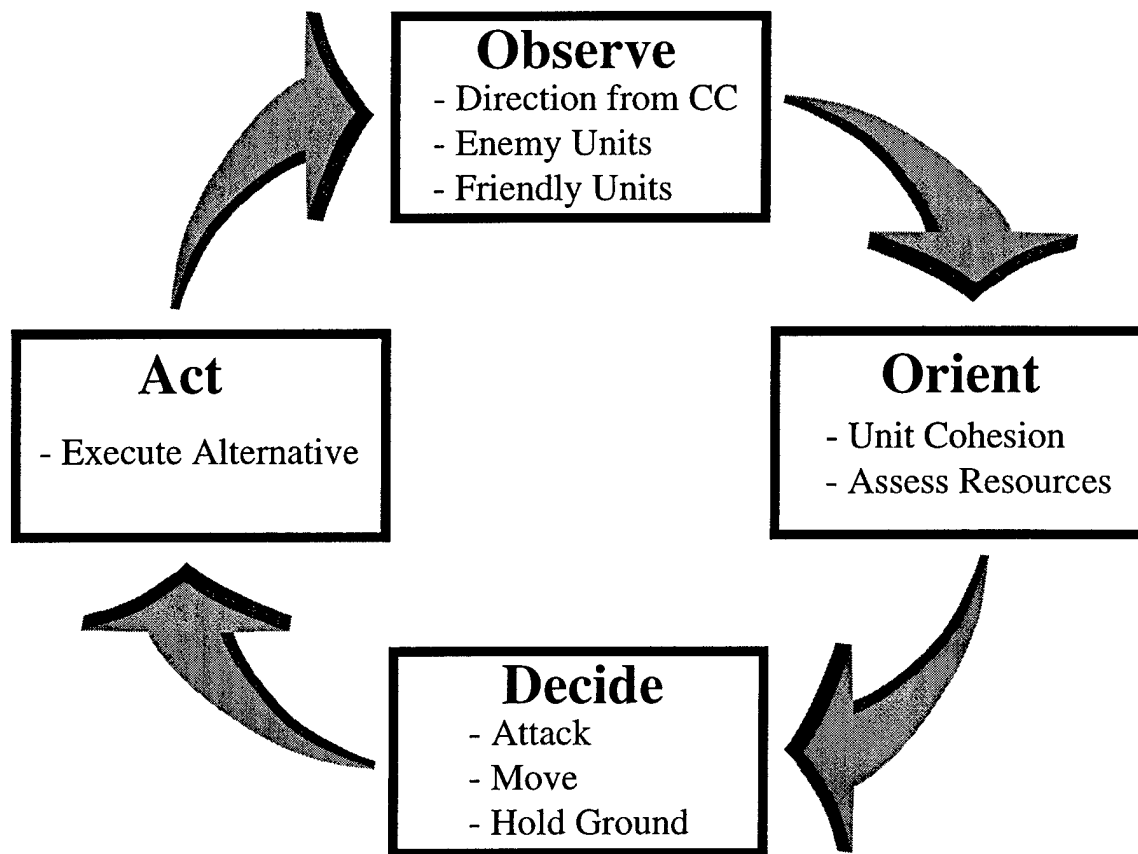


Figure 22. Ground Unit Decision Cycle

The defensive aircraft pilot does not attack enemy resource targets. The pilot only engages in air-to-air combat but can attack IADS sites if encountered. The pilot carries out these tasks in an F-16-like aircraft (Figure 21) equipped with precision guided air-to-surface weapons such as the AGM-65 Maverick infra-red guided missile. Like the attack pilot, for air-to-air engagements, the defense aircraft are equipped with a weapon such as the AIM-120 fire-and-forget AMRAAM (Advanced Medium Range Air to Air Missile). Unlike the attack pilots, however, the defensive aircraft pilots do not engage ground units.

3.3.5 Ground Units

The ground units represent elements of a single mechanized infantry division. HITM groups the elements and does not model specific pieces of equipment within the division. HITM does assume availability of necessary equipment to defend against air and ground attack, as well as equipment to carry out offensive operations. The objective for each ground unit is to proceed towards the enemy airbase as directed by the Commander. The decision process for the ground units is depicted in Figure 22.

As with the pilots, each ground unit is unique. Each unit has a level of unit cohesion which is initialized randomly but changes throughout the duration of the battle. The unit cohesion level impacts the unit's effective probability of kill as well as the unit's rate of movement. Each unit's decision process begins in the observe phase by implementing the ground posture direction from the Commander. Then, the ground units gather intelligence related to enemy and friendly ground unit locations. The ground units synthesize this data in the next phase, orient, for use in conducting operations. Also in the orient phase, the ground units assess available resources to include communications, fuel, and ammunition.

Using the synthesized information from the orient phase, influenced by the Commander's posturing direction, the ground units move to the next phase, decide. The ground units can choose from among three alternatives. The ground units can attack, move towards the objective, or hold ground. If an enemy ground unit is within firing range, the ground units will attack. The probability of kill for an attack is based on ammunition, communications, and unit cohesion. In addition, the ground unit's effective probability of kill is increased if friendly ground units are within communications range. A successful

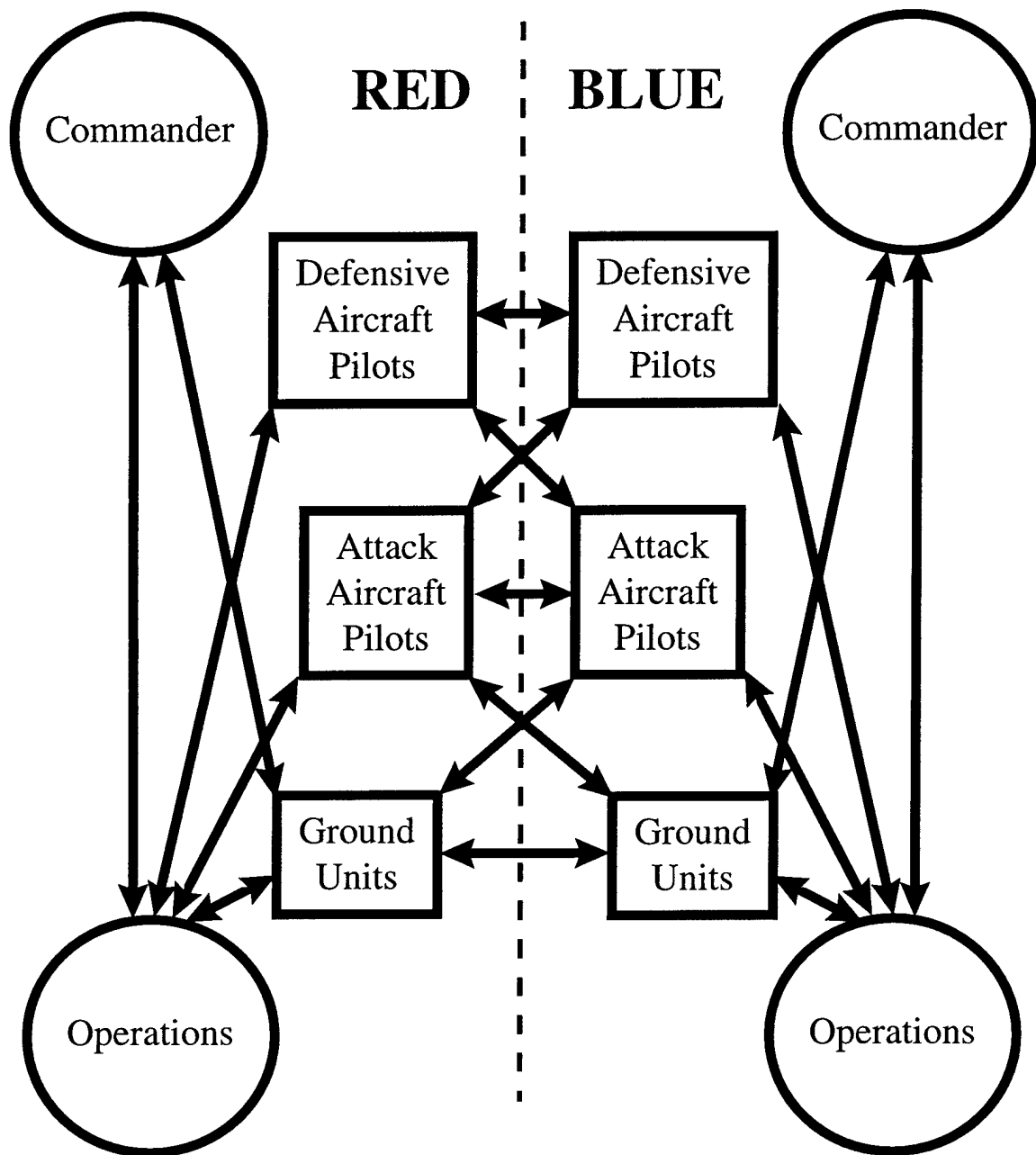


Figure 23. HITM Agent Interaction Diagram

ground unit attack results in pushing the enemy back. The distance the enemy is pushed back depends on the enemy unit's cohesion. If the ground units are not within firing range, but are within friendly communications range as directed by the Commander, the units can advance. Rate of advance depends on fuel availability and unit cohesion. If the

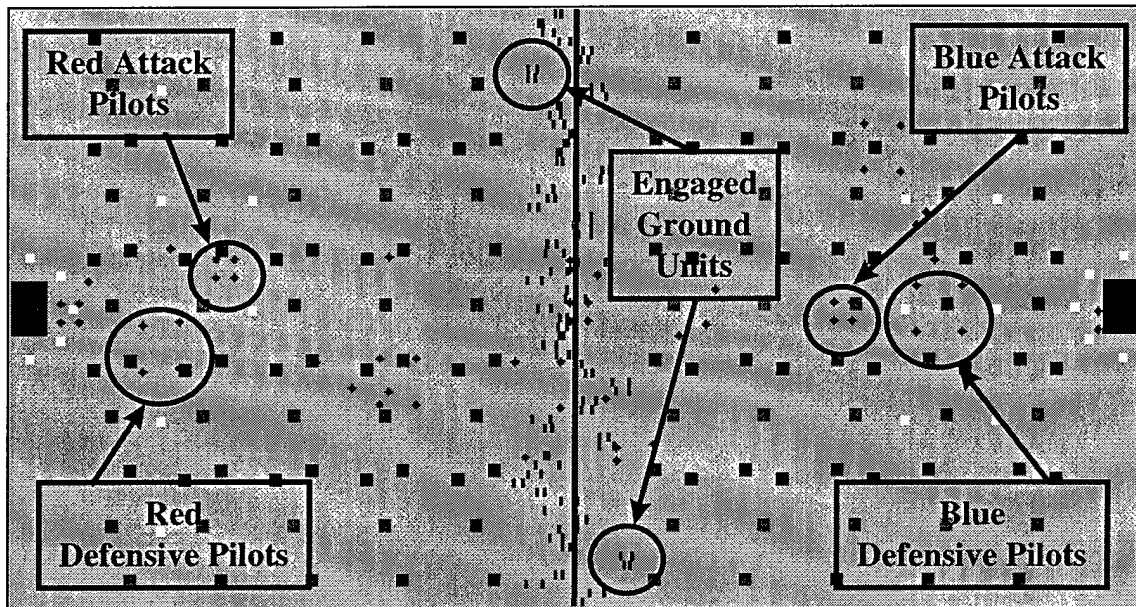


Figure 24. HITM Screen Shot

ground units are not within firing range and are not within the communications range prescribed by the Commander, the units will hold ground.

Every unit has the option to call for CAS at any time. The decision to call for CAS is based on unit cohesion. Units with high unit cohesion, will recognize the need for help faster than a unit with low cohesion. This results in units with higher unit cohesion having more room for delay between when a unit recognizes it needs help and unit destruction. A CAS attack on an enemy ground unit results in reducing response time of the unit. Choosing among the above alternatives, the ground units move into the final phase, act, to execute their chosen alternative. Additional details on agent interactions are summarized in the following section.

3.4 HITM Simulation & Limitations

The outcome of the HITM simulation is driven by agent interaction. The diagram in Figure 23 summarizes these interactions. For simplicity, the diagram only shows the interaction among agents. However, a critical interaction occurs between the agents and the environment. Specifically, all agents require resources to carry out their duties. In addition, the attack aircraft pilots and the ground units interact with the adversary's resources in an attempt to destroy them. Figure 24 shows how the agent interactions are depicted in HITM.

Multithreading plays a critical role in modeling a Complex Adaptive System composed of autonomous agents and was used to develop HITM. The JAVA programming language accommodates threads. One drawback to multithreading is that JAVA multithreading is platform dependent [Deitel 1998:p692]. This implies that results from one simulation run should only be compared to other simulation runs made on the same computer. This problem is further compounded by loss of control over a population of threads in terms of sequencing. This problem is only a concern when attempting to use common random numbers. JAVA produces random numbers using a linear congruential formula and accommodates input seeds to synchronize common random numbers between simulation runs. The problem with multithreading is that each thread is an autonomous program which is controlled by the computer's operating system. Thus, one cannot control the order in which threads grab random numbers.

Other HITM assumptions and limitations are listed below:

- Enemy objectives are clearly known
- Military leadership cannot be targeted directly; only their processes
- Population is not a possible target

- Agents do not evolve or learn; they only react
- Each opponent knows the location of the adversary's COG at the outset
- A pilot's OODA Loop is not impacted by strategic attacks
- HITM focuses on the operational level (military targets)
- Achieving military objectives imply achieving political objectives

Despite these limitations, HITM provides a means to explore the relationship between strategic effects and OODA Loops. The investigation is carried out by using HITM in a series of experiments.

4. Experiments

The Battlefield is a scene of constant chaos. The winner will be the one that best controls that chaos, both his own and that of his enemy.

-- Napoleon Bonaparte

Experiments using HITM were conducted to study how two forces fare when pitted against one another. These experiments have a dual focus. The primary focus is to examine the simulation outcome and determine why it occurred, when the forces are equally matched. A secondary focus is to investigate initial conditions necessary to drive desired outcomes. Table 4 lists the measures of performance (MOPs) used in the study. Each of these were recorded for each opponent at one second intervals for the duration of the simulation runs.

4.1 Equal Fight

The first experiment using HITM investigates two equally matched opponents. The two opponents start off with equal force structure and resources. However, as the fight progresses, the balance is tipped and one side gains the advantage. The goal of this experiment is to determine when and under what circumstances one side gains the advantage. Another important aspect examined is if a slight disadvantage for one side results in a brute force push to the objective or if it "snowballs" into total collapse.

Table 4. Measures of Performance

Command & Control Resources
Organic Essential Resources
Infrastructure Resources
Forward Line Of Troops
Commander Decision Cycle Time
Operations Decision Cycle Time
Ground Unit Decision Cycle Time

Table 5. Basic Statistics of Equal Fight Simulation Runs

Wins:	
Red	17
Blue	13
Simulation Run Time (s)	
Mean	106.63
Median	97.50
Maximum	184.00
Minimum	69.00
Standard Deviation	29.27

4.1.1 Results and Analysis

Thirty runs were conducted under the equal fight scenario. It was assumed that thirty runs would provide a representative sample of possible outcomes HITM would generate under equal fight conditions. Table 5 highlights the basic statistics for the thirty runs. In addition, Figure 25 shows the loser-to-winner ground win ratio and the aircraft lost ratio for each run. The purpose of Table 5 and Figure 25 is to show that the fight was fair, but more importantly, to show that even though no simulation parameters were changed between runs, there was a wide variation in how a given side achieved its objective. Now the task becomes how to analyze this wide distribution among runs and find information that not only applies equally to all thirty runs but provides insight into how a given side was able to achieve victory. Since the concern is not with who won but

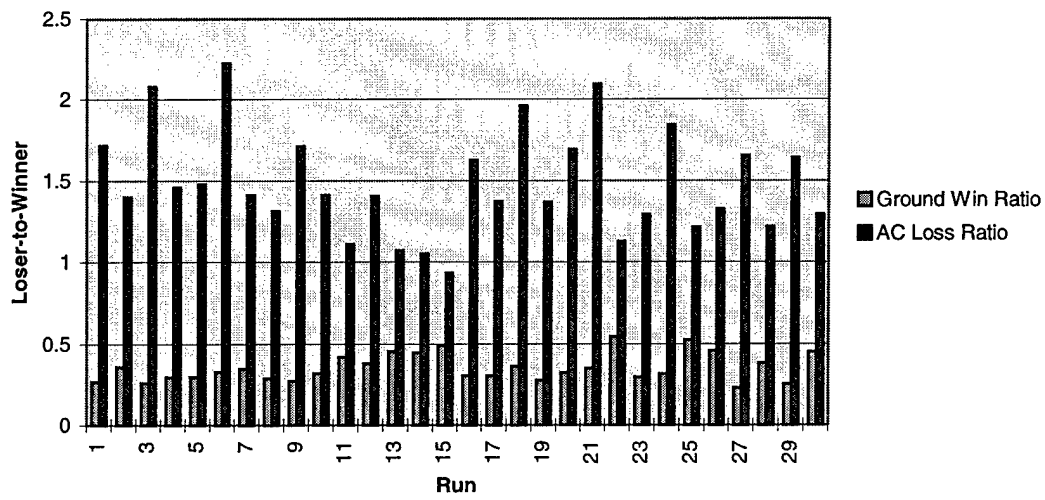


Figure 25. Equal Fight Output Variation

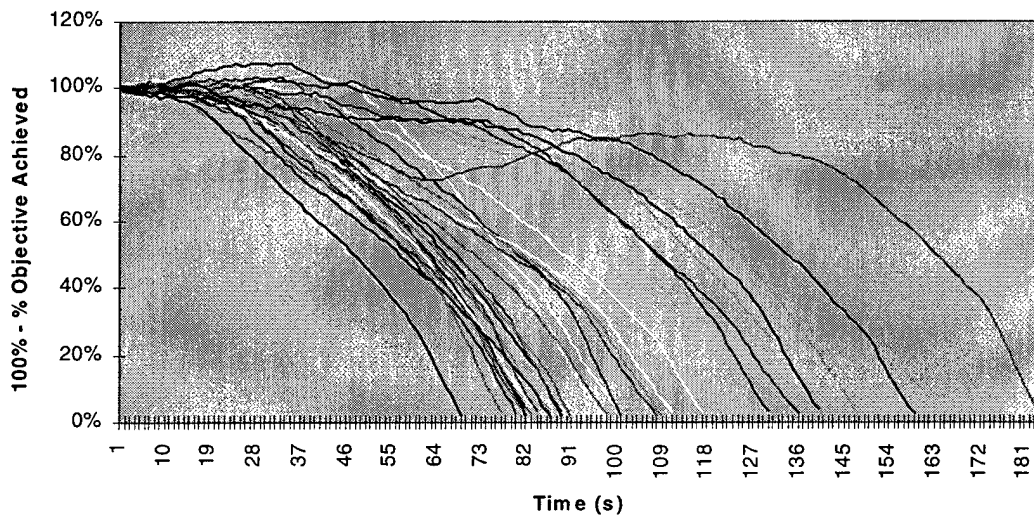


Figure 26. Paths to Victory

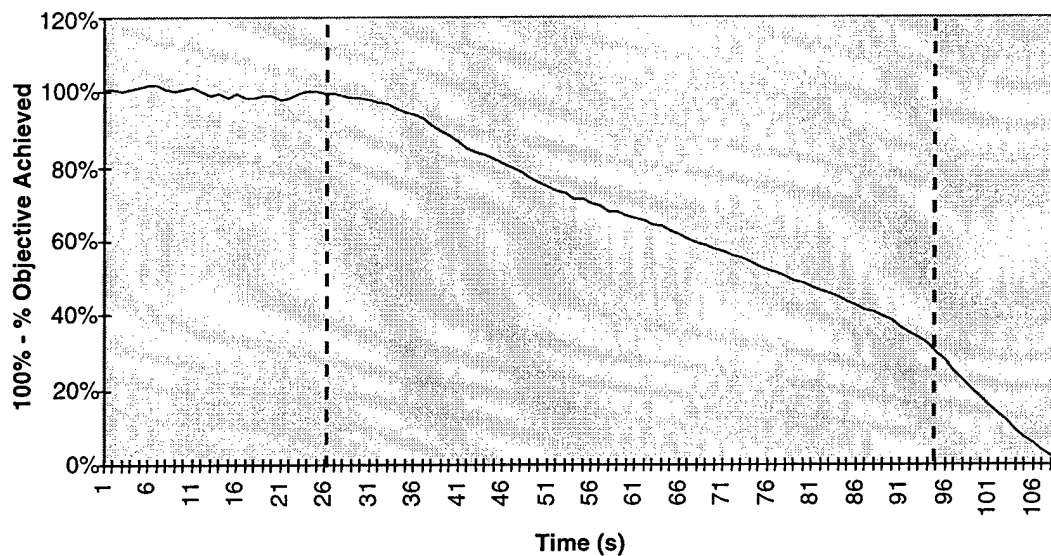


Figure 27. General FLOT Path Characteristics

why they won, the winner is compared to the loser for all thirty cases regardless of whether red or blue won.

HITM uses Forward Line Of Troops (FLOT) location to determine when one opponent has achieved its objective. For this reason, analysis of the output will also use FLOT location as a starting point in determining why one side was able to achieve victory and the other side was not. Figure 26 displays the various FLOT paths followed over the thirty simulation runs.

Figure 26 also shows the wide variation in the ways opponents achieved their objective as well as the wide variation in the time required to obtain the objective. Despite their differences, there are similar characteristics between the paths. Each path can be divided into three regions. The first part of each path starts out relatively flat. The second region can be defined where the path becomes strictly decreasing and the third

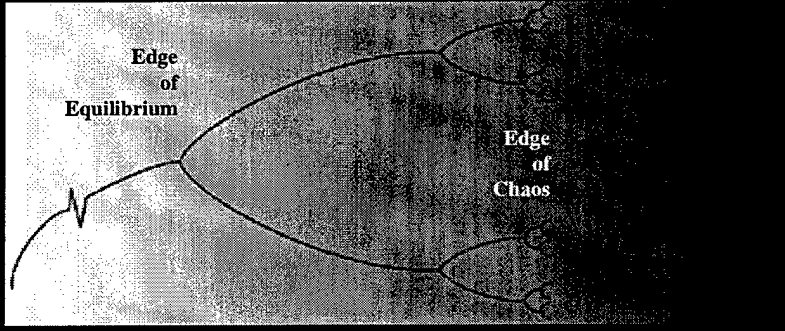
Type	Linear	Nonlinear	
Regime	Equilibrium	Complexity	Chaos
Character	Stable - Disturbance dies out - Damage is local	Emergence - Poised to adapt and evolve - Damages are limited	Turbulence - Disturbances propagate - Destruction
Pattern			

Figure 28. Regions of a Nonlinear System [Czerwinski 1998:p25]

region emerges where the path slope drops. Figure 27 highlights one path to emphasize these regions.

Czerwinski [1998] suggests all nonlinear systems can be characterized by three regions (Figure 28) and links these regions to the battlefield. The first region is Equilibrium where damages inflicted by the enemy are local and their effects die out. The second region is Complexity. In this region, the damage inflicted by the enemy requires adaptation in order to overcome the effects. The third region is Chaos where damage inflicted by the enemy propagates and eventually results in destruction.

The characterization of the regions Czerwinski describes are evident when watching the HITM simulation and are also evident in the single FLOT path (Figure 29). The first region, Equilibrium, evolves since both opponents start with equal capabilities and the effects of attacks made by either side die out. Even after the start, the Equilibrium phase is maintained since attacks made by either side seem to only have local effects which die out. However, if an opponent is not able to overcome attacks, the

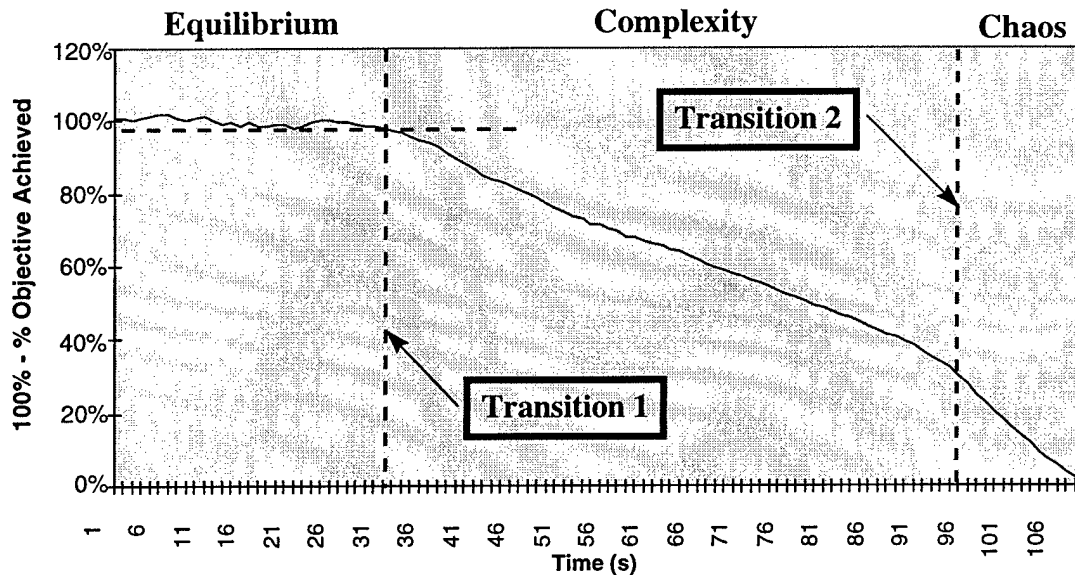


Figure 29. FLOT Regions

opponent will fall into the Complexity region. Once in this region, an opponent is put in a position of reacting to the other opponent's actions. This region can be doubly damaging since resources are diverted from offensive to defensive operations. As shown in all the FLOT paths in Figure 26, if an opponent is not able to adapt and push back into the equilibrium region, the effects of attacks will propagate, eventually causing the opponent's total collapse. Using this common framework for all the simulation runs, the transition boundaries should highlight areas in the data indicating conditions necessary for one opponent to push another opponent into a nonlinear region and achieve victory.

Each of these boundary regions was identified for each of the thirty runs. The Equilibrium to Complexity boundary was defined where the FLOT path becomes strictly decreasing with a point lower than any point in the equilibrium region (Figure 29). The Complexity to Chaos boundary was defined where the FLOT path slope drops. The MOPs were then collected at these boundary regions. In addition, the total resources

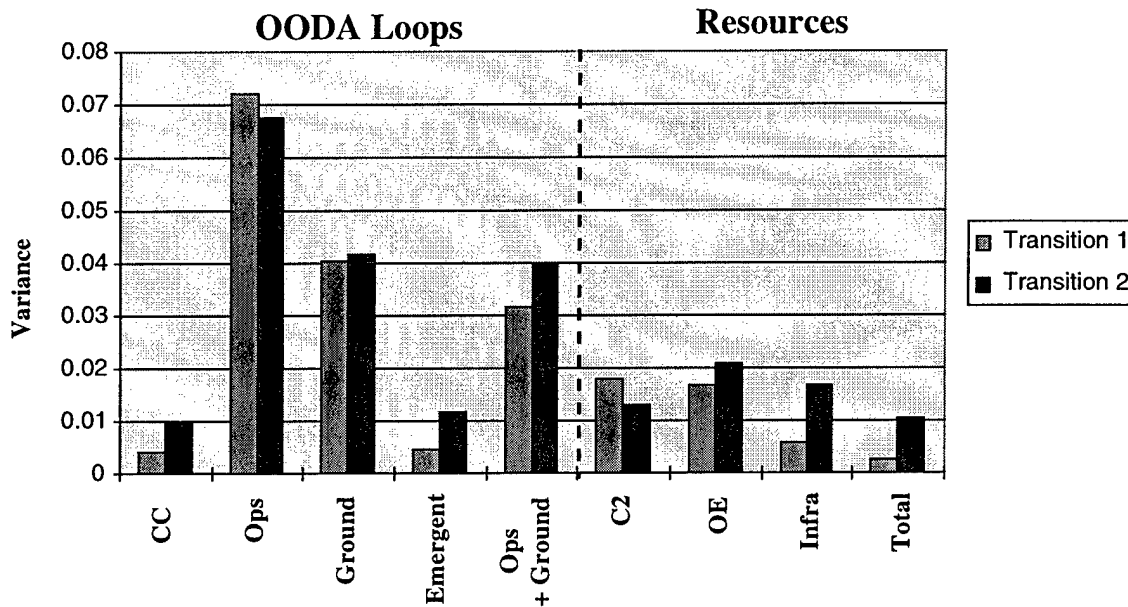


Figure 30. MOP Ratio Variance at Transition Boundaries

available was derived by summing the Command and Control resources, Organic Essential resources, and the Infrastructure resources. In a similar manner, the emergent decision cycle or Emergent OODA Loop time was derived by summing the decision cycle times for the Commander, Operations, and the Ground Units. Since each simulation run had a different duration and the time differences would bias comparison of MOPs between simulation runs, the MOPs were collected as a ratio of loser to winner for the resources and as a ratio of winner to loser for the decision cycle times. This collection procedure normalized the data between simulations runs. To identify the most robust indicator among the MOPs, the variances of the ratios were calculated.

Figure 30 displays variances of the MOP ratios at each of the transition regions. The variances included are the winner to loser ratio for the Commander OODA Loop (CC), Operations OODA Loop (Ops), average Ground Unit OODA Loop (Ground), and the sum of the three (Emergent). In addition, the loser to winner ratio variance was

calculated for Command and Control resources (C2), Organic Essential resources (OE), Infrastructure resources (Infra), and the sum of the three (Total).

The variances in Figure 30 reveal many important insights. First, looking at the resource related ratios, the variance of the total resources is significantly less when compared to the elements composing the total (C2, OE, and Infra). This is true for both transition points. This result suggests that the amount of total resources available is more important than any individual resource implying that no single resource was consistently responsible for an opponent losing. The results of the thirty runs indicate that 95% of the time the transition from Equilibrium to Complexity occurred when the ratio of the loser's total resources to the winner's total resources was between .8877 to .9266. The results also indicate that 95% of the time the transition from Complexity to Chaos occurred when the ratio of the loser's total resources to the winner's total resources was between .5247 to .6019.

The interpretation of the OODA Loop times is not as straightforward. Figure 30 seems to indicate the Commander's OODA Loop time is more significant than the Operations OODA Loop and average Ground Unit OODA Loop times. However, before discounting the importance of the Operations OODA Loop and average Ground Unit OODA Loop times, a reduced Emergent OODA Loop was calculated without the Commander's time included and the variance was calculated. The variance of this reduced Emergent OODA Loop is less than the variance of the individual components. This implies the Operations OODA Loop time and the average Ground Unit OODA Loop time are out of synch with one another. This reveals an emergent property. That property being that the winner compensates for weaknesses within its organization or within its

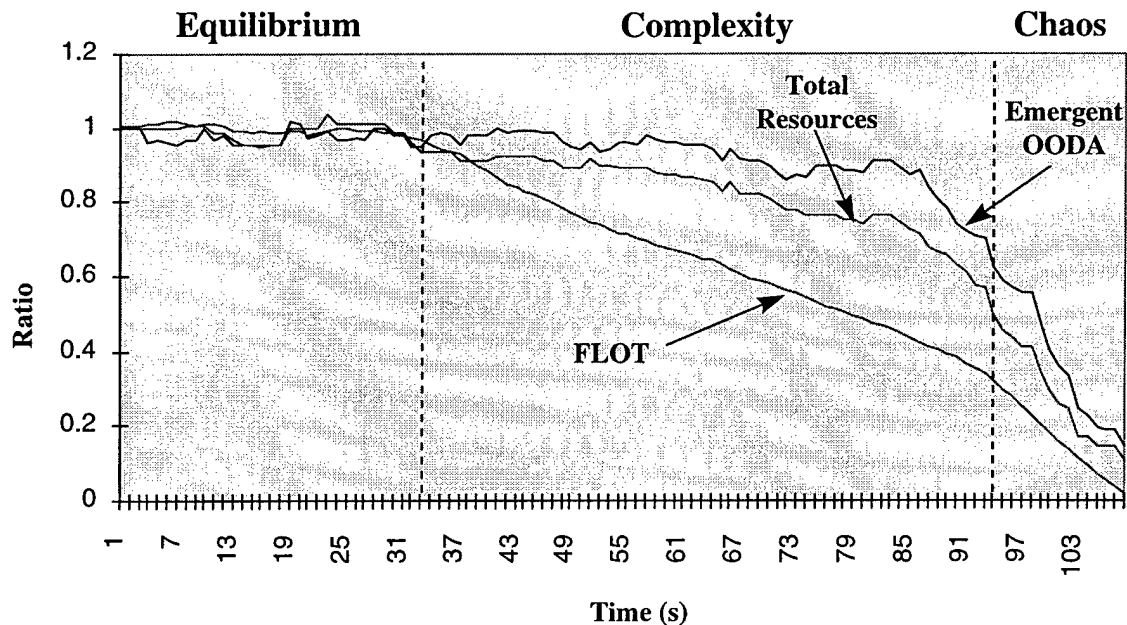


Figure 31. OODA Loop, Resources, and Objective Relationship

Emergent OODA Loop. For example, if the ground war is not going well, the winner compensates for ground weakness in the air war or compensates for air weaknesses on the ground. Based on this information, the appropriate OODA Loop MOP is the full Emergent OODA Loop since it contains the significance of the Commander's OODA Loop, as well as the synergistic information contained in the Operations OODA Loop and Ground Unit OODA Loop. The results of the thirty runs indicate that 95% of the time the transition from Equilibrium to Complexity occurred when the ratio of the winner's Emergent OODA Loop time to the loser's Emergent OODA Loop time is between .8815 to .9328. The results also indicate that 95% of the time the transition from Complexity to Chaos occurred when the ratio of the winner's Emergent OODA Loop time to the loser's Emergent OODA Loop time is between .5723 to .6527.

The Emergent OODA Loop time is linked to resources – time to get intelligence data, time to get fuel, and time to get resupplied with ammunition. To confirm this

assumption, a 2-sample t-Test with unequal variances was conducted between the normalized total resources values and normalized Emergent OODA Loop values. The comparison at the Equilibrium to Complexity boundary resulted in a p-value of .9929. The comparison at the Complexity to Chaos boundary, however, although still statistically different, only resulted in a p-value of .0756. The Complexity to Chaos value can be attributed to the fact that other factors besides resources, such as base attacks and CAS attacks, impact OODA Loop times as the simulation progresses. Figure 31 displays an example, for a single run, of the relationship between FLOT position, total resources, and the Emergent OODA Loop.

The purpose of the above Equal Fight analysis was to determine when and under what circumstances one side gains the advantage. The analysis shows the winner gains the advantage when one opponent is pushed from Equilibrium to Complexity and this occurs when one opponent's total resources are approximately 90% of the winner's total resources. The significance of the total resources implies there are many ways to achieve the objective in terms of target sets attacked. The key element being that the total resources of one opponent is reduced to 90% of the other opponent's resources. It should be pointed out that there is a temporal aspect to this metric. Achieving the 90% measure in absolute terms is not enough. The 90% measure must be maintained for a period of time. During this time, the opponent with the disadvantage has a brief opportunity to push the situation from Complexity back into Equilibrium. One way an opponent could achieve this is if the opponent has the emergent characteristic of being able to compensate for weaknesses within its organization. If the opponent does not have this emergent behavior, the decreased resources lead to longer delays to get intelligence, fuel, and

ammunition resulting in an increased Emergent OODA Loop. The longer Emergent OODA Loop magnifies the disadvantage eventually causing total collapse. In addition, the fact that effects of destruction of vital targets is most evident when examining the emergent OODA Loop, or the whole enemy system, implies strategic effects is a type of emergent phenomena.

Figure 30 indicates total resources is more significant than any of the individual components. However, the figure does imply differences in variance among the three resource components (Command and Control, Organic Essentials, and Infrastructure). Nicholls [1994] suggests a model such as HITM could be used to determine which initial conditions have the most profound effect on a system which in turn could help identify centers of gravity. The next section explores this topic.

4.2 Sensitivity to Initial Conditions

The second experiment using HITM investigates the same opponents from the first experiment, however, one opponent (Red) is started with various levels of degraded resources. The goal of this experiment is to determine the impact of three resource types (Command and Control, Organic Essentials, and Infrastructure) on Red to determine Red's centers of gravity. A secondary issue investigated is the temporal aspects of resources to see if there is a time when a particular resource becomes a center of gravity.

4.2.1 Results and Analysis

For each of the three resources (Command and Control, Organic Essentials, and Infrastructure) the starting available resources for Red was varied at 87%, 80%, 73%, 67%, and 60% of the total resources. Ten runs were conducted at each of the 15 design

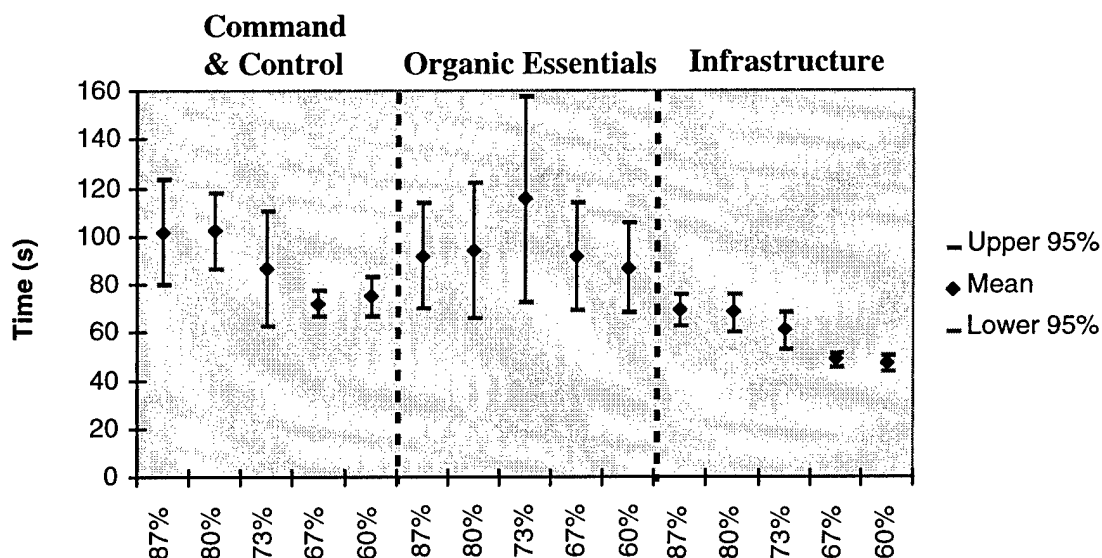


Figure 32. Time to Achieve Objective

levels for a total of one-hundred fifty runs. The measures used for comparison were the time to achieve the objective and the ratio of red ground wins to blue ground wins. The results are shown in Figures 32 and 33.

These figures provide insights between groups of resources as well as insights within a specific group. First, comparing between the three groups of resources, one sees that no one resource is statistically different across the board. However, the infrastructure resource is the only group that has elements that are statistically different from the other two. This implies that infrastructure targets are strategically more significant than C2 and organic essential targets within the HITM battlespace. Next, looking within each resource group, there is an interesting effect between the 3rd (73%) and 4th (67%) elements. This effect is mainly seen in the C2 and infrastructure resource groups. There is a drop in the mean as well as the variance between these 3rd and 4th elements. This

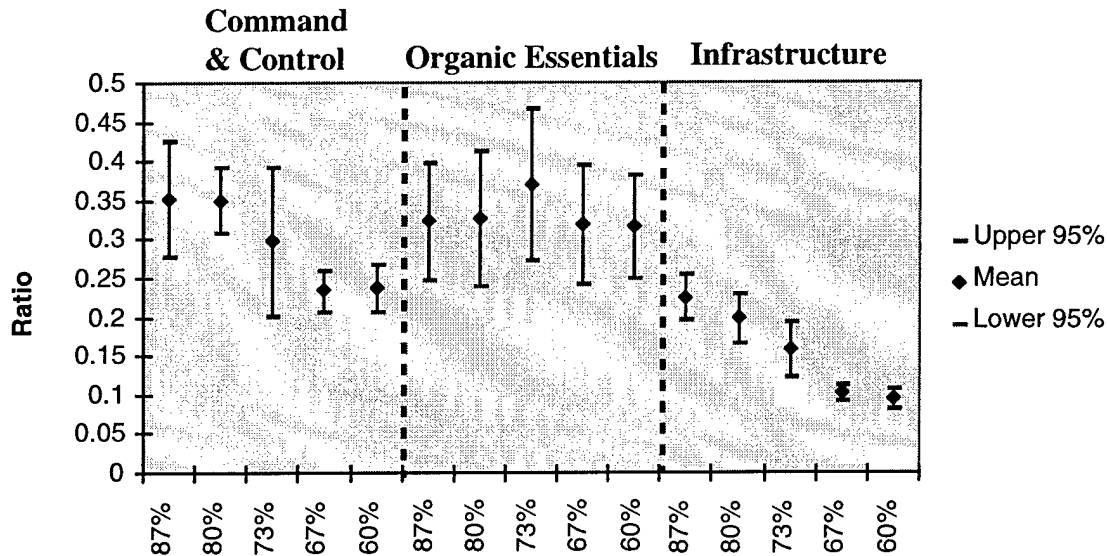


Figure 33. Ground Win Ratio

effect is explained by the first experiment. The 3rd and 4th elements contain the 70% resource level. This 70% resource level equates to 90% of total resources, which was shown to be the critical point where an opponent could potentially be pushed from a state of equilibrium into a state of complexity.

Results of analysis of the elements within groups implies an opponent that starts off with C2 or infrastructure resources below 70%, starts the battle in a state of complexity versus a state of equilibrium. This effect is clearly seen in the infrastructure resource group where the last two elements are statistically different from the first three. The effect is also evident in the C2 resource group, however, the last two elements are not statistically different from the 3rd element. This can be attributed to the small number of runs made (10) for all elements as well as an outlier within the 3rd C2 element. However, the drop-off is clear when comparing variances of the last two elements to the first three. The variance of the last two elements is smaller than the variance of the first three

elements for both C2 and infrastructure targets. The fact that the organic essentials group does not have elements that are statistically different from the other two and the fact that a drop off does not occur after the 70% level suggests the organic essential targets are insignificant relative to the C2 and infrastructure targets within the HITM battlespace.

The reduced variance between the 3rd and 4th elements also has further meaning. Huxley [1998] suggested overwhelming force could significantly linearize a conflict. By starting an opponent off with 70% of C2 or infrastructure resources, the opponent is effectively overwhelmed and begins the battle in a state of complexity. The asymmetry between opponents results in smaller variance of potential outcomes yielding a more linearized, predictable outcome.

5. Conclusion

If you know the enemy and know yourself, you need not fear the result of a hundred battles.

-- Sun Tzu

5.1 Strategic Effects and OODA Loops

The HITM experiment results depict a cascading deterioration in force effectiveness and eventual total collapse resulting from destruction of vital targets. This outcome is consistent with the expected results of strikes against centers of gravity defined in Air Force doctrine. The foundation of HITM is built upon the classical military theories of Clausewitz as well as the modern theories of Warden and Boyd. In addition, HITM is implemented using advanced mathematical concepts from Complex Adaptive Systems and Chaos theory.

The purpose of exploratory models, such as HITM, is to assist in reasoning about systems, such as war, that contain significant uncertainty. HITM uses a bottom-up approach focusing on the actual processes of conducting military operations and the individual agents carrying out those processes versus an aggregated, top-down approach using theoretical, linear laws of combat such as Lanchester equations. The process oriented approach allows for capturing the interaction of the entities among themselves and interaction of the agents with the environment. This approach in turn allows for capturing Clausewitz's concept of friction, which over time causes plans to deviate from their original intent and slows down the rate at which an opponent can conduct military operations. Capturing the concept of friction is important because it is closely related to

strategic effects. Air attack has the effect of interrupting or slowing the rate at which the enemy can conduct military operations, or in other words, air attack induces friction on the enemy.

The HITM experiments demonstrate how air strikes slow down each agent's process of waiting on information, fuel, and/or ammunition. Even a small slowdown for each individual agent accumulates causing a significant slowdown at the organizational level. As the HITM experiments demonstrated, the key to victory lies in being able to operate inside the opponent's organizational level process or Emergent OODA Loop. In addition, analysis of HITM output suggests OODA Loops combined with an agent-based modeling approach is an effective way to simulate strategic effects at the operational level of war.

5.2 Contributions of Research

This thesis explores the nature of strategic effects and how to capture them in models. The research links the concept of strategic effects to classical military theories. The linkage is confirmed by using modern military theories and concepts from the fields of Complex Adaptive Systems and Chaos theory in a simulation model -- the Hierarchical Interactive Theater Model (HITM). Analysis of experiments using HITM, suggests OODA Loops in combination with an agent-based modeling approach, is an effective way to simulate strategic effects at the operational level of war.

5.3 Areas for Continued Research

While HITM demonstrated that strategic effects can be simulated, it has several limitations. Areas of continued research to expand HITM's capabilities include:

1. Agent Evolution: HITM incorporates reactive agents. A logical next step is to build a model in which agents learn and evolve. The field of genetic algorithms offers a promising way to incorporate adaptive learning.

2. Multi-Threaded Agents: Agents in HITM each operate on a single thread. Implementing multiple threads per agent would allow agents to conduct tasks in parallel, making them more realistic.

3. Complex Hierarchy: Each opponent in HITM has a very simplistic military chain-of-command. Constructing a more complex hierarchy or different chain-of-command structure might reveal benefits of information flow through different hierarchy structures.

4. Military Operations Other Than War: The HITM scenario is based on a "traditional" military conflict. However, the future will likely see the military increasingly involved in combating terrorists, drug cartels, and other "enemies without borders". Research needs to be conducted to determine the impact of strategic effects on these opponents and how the effects should be modeled.

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